# Project Casper

## Preliminary Design Review (PDR)

Purdue University 2020

2604 Bristlecone Dr.
West Lafayette, IN 47906
Purdue Space Program

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## Acronyms and Abbreviations

| Acronym / Abbreviation | Definition |
|---|---|
| PSP | Purdue Space Program |
| SL | Student Launch |
| AGL | Above Ground Level |
| CDR | Critical Design Review |
| FAA | Federal Aviation Administration |
| FEA | Future Excursion Area; Finite Element Analysis |
| FMEA | Failure Modes and Effects Analysis |
| FRR | Flight Readiness Review |
| LRR | Launch Readiness Review |
| NAR | National Association of Rocketry |
| NASA | National Aeronautics and Space Administration |
| PDR | Preliminary Design Review |
| R&D | Retention and  Deployment; Research and Development |
| TRA | Tripoli launch vehicle Association |
| R&VP | Requirements and Verification Plans |
| GCS | Ground Control Station |
| FOS | Factor Of Safety |

# 1. PDR Report Summary

The information in the following sections summarizes who we, the 2020 PSP-SL team, are as a team, our mentor, general launch vehicle details, and various other basic statistics.

## 1.1. Team Summary

| | |
|---|---|
| **Team Name** | PSP-SL (Purdue Space Program - Student Launch) |
| **Mailing Address** | 2604 Bristlecone Dr., West Lafayette, IN 47906 |
| **2020 Team Mentor** | Victor Barlow |
| **2020 Mentor Contact Information** | vmbarlow@purdue.edu \| (765) 414-2848 (Cell) |
| **2020 Mentor TRA / NAR Certifications** | NAR 88988, TRA 6839 TAP, Level 3 Certified |

## 1.2. PSP-SL 2020 Executive Board

| Position | Name | Email |
|---|---|---|
| **Project Manager** | Luke Perrin | lperrin@purdue.edu |
| **Assistant Project Manager** | Michael Repella | mrepella@purdue.edu |
| **Safety Team Lead** | Noah Stover | nstover@purdue.edu |
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| **Payload Co-Team Lead** | Hicham Belhseine | hbelhsei@purdue.edu |
| **Avionics & Recovery Team Lead** | Katelin Zichittella | kzichitt@purdue.edu |
| **Business Team Lead** | Natalie Keefer | nkeefer@purdue.edu |
| **Social & Outreach Team Lead** | Skyler Harlow | sharlow@purdue.edu |
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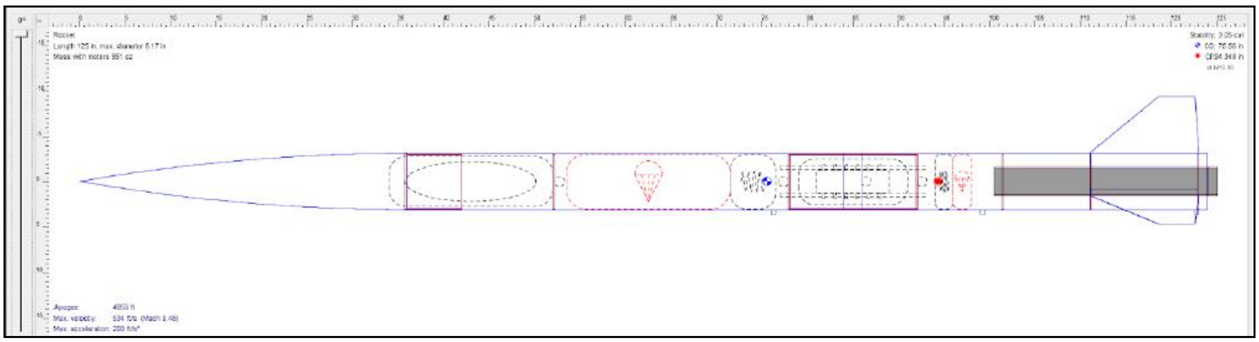
| **Construction Team Mentor** | Zach Carroll | carrollz@purdue.edu |

## 1.3. Launch Vehicle Summary

The following information provides a summarized version of the launch vehicle to be constructed by the PSP-SL team for this year's competition.

### 1.3.1. Launch Vehicle Size and Mass

The 2020 PSP-SL launch vehicle has a 6” inner diameter body tube. The team will utilize a 5:1 Von Karman nose cone design. The launch vehicle is 125” long (tip to tail), including a 2” long switch band, a 48” long upper airframe, a 38” long lower airframe, a 1” long retainer, and a 36” long nose cone. The fins are trapezoidal with a max height of 6.25” from the exterior of the airframe, a tip chord of 4”, a root chord of 12”, and a fin sweep angle of 50.5°. The predicted mass of the launch vehicle is 53.2lbm. Around 16lbm of this will come from the nose cone, body tubes, three fins and the witch band, which are composed of G12 filament-wound composite fiberglass. The rest of the weight will come from internal components, such as a UAV payload system, parachutes, a recovery system, the avionics bay, and a camera payload.



### 1.3.2. Preliminary Motor Choice

PSP-SL has tentatively selected a Cesaroni (CTI) L1115 motor to propel thelaunch vehicle. This is a 75mm (2.95”) x 62.1cm (24.44”) motor with a total loaded weight of 4404g (9.70lbm) and propellant weight of 2394g (5.27lbm). With a burn time of 4.5s, the thrust of this motor averages to 1119.0N (251.56lbf)  and reaches a maximum of 1713.3N (385.16lbf), which comes to a total impulse of 5015.0N-s (1127.41lbf-s). The specific impulse (Isp) of the CTI L1115 motor is 213.6s. It is important to note that the motor choice will not be locked in until CDR as per the rules of the competition.

### 1.3.3. Recovery System

The recovery system consists of a coupler sealed with bulkheads and located between the upper and lower airframe of the launch vehicle and the 2” switch band which separates them. This is the avionics bay. Its purpose is to house the primary and redundant altimeters and their batteries. These will be mounted to a 3D-printed sled that will slide onto two threaded rods that attach to the bulkheads on either side of the avionics bay. Wires will join the altimeters to their corresponding rocker switches in the switch band and the e-matches to the ejection charges located on the exterior of the bulkheads. Fine-grain black powder is the ejection charge type that will be used. Finally, the main and drogue parachutes will be attached to forged I-bolts on the upper and lower bulkheads, respectively.

## 1.4. Payload Summary

***“The Friendly Ghost” - Autonomous Unmanned Aerial System***

The chosen payload is comprised of an unmanned aerial vehicle (UAV) and a portable ground control station. The UAV is capable of fully autonomous or remotely piloted flight and will be equipped with a lunar ice mining and storage system. The ground control station (GCS) will control and monitor the UAV and launch vehicle telemetry. The UAV will be mechanically stored and retained in the launch vehicle during flight and recovery, and upon landing will autonomously move to a recovery zone to extract and store an ice sample.

# 2. Changes Made Since Proposal

## 2.1. Changes Made To Vehicle Criteria

There have been extensive modifications to the initial design of the full scale launch vehicle since the proposal. The first significant design change is that the lower airframe was extended by 8”. This change allows for more room in the lower airframe for the motor, the drogue parachute, and drogue parachute shock cord, and parachute heat shielding. The second major design change to the launch vehicle is that the team changed the fin design from having a sweep angle of 57.2° and sweep length 8” to a sweep angle of 50.5°, and a sweep length of 7.593”. The height of the fins was also increased by 1.1”, and the tip chord length was shortened from 5” to 4” (tip chord was shortened in order to reduce induced drag and maintain energy to gain a few feet in apogee). This change was made so that the overall stability of the launch vehicle stays between 2.7 and 3.3 cal. The team also merged the lower and middle airframe sections and placed the avionics bay between the upper airframe section and the lower airframe. The purpose of this is to decrease the overall weight of the launch vehicle and create more space for the main parachute compartment to ensure that the main parachute can comfortably fit inside the launch vehicle. A fourth significant change made was that the team extended the nose cone from 30” to 36”, which, in conjunction with the new fin design, helps keep the stability of the launch vehicle between 2.7 and 3.2 cal. This also allows the UAS payload system to have more volume to ensure active payload retition.

There was a major change in the recovery system of the launch vehicle. Using an updated projected ratio of the weight of the heaviest section of the launch vehicle to the weight of the entire launch vehicle (31%), MATLAB code was written to determine the maximum starting weight of the launch vehicle in order for the heaviest section to land with a kinetic energy of less than 75ft-lbf (as specified in the NASA requirements). With the original parachute choice (Skyangle Cert-3 XL), the maximum starting weight would be 43lbm. With a parachute one size larger that is already in the team’s possession (Skyangle Cert-3 XXL), the maximum starting weight would be 56.5lbm. Since the current projected total weight of the launch vehicle is about 53.2lbm, the Skyangle Cert-3 XL would no longer be sufficient as the main parachute. However, the Skyangle Cert-3 XXL would provide a low enough landing kinetic energy for the heaviest section of the launch vehicle. Therefore, the choice was made to switch to the Skyangle Cert-3 XXL as the main parachute in the launch vehicle design.

Because the Skyangle Cert-3 XXL is much larger that the Skyangle Cert-3 XL, the projected main deployment altitude was increased from 700’ AGL to 800’ AGL to allow it more time to fully open before the required full deployment altitude of 500’ AGL, as specified in the NASA requirements. It was also determined that additional swivels located between the quick links attached to the parachutes and the forged I-bolts attached to the bulkheads in the avionics bay would not be required because both the drogue and main parachutes come with the same swivels already attached.

A secondary Avionics & Payload change is that instead of placing the secondary payload (camera system) into a lower coupler, it will be placed in the avionics bay so that a lower coupler is not needed, which saves on system mass. To accommodate the volume of the camera in the bay, the avionics sled will be separated from the battery compartment so that the camera can be placed directly underneath the switch band for optimized recording capabilities.

## 2.2. Changes Made To Payload Criteria

There have been minimal changes to the design of the primary payload experiment since the submission of the proposal. The design of all payload subsystems have matured, with leading designs selected from many of the alternatives presented in the proposal.

## 2.3. Changes Made to Project Plan

There have been minimal changes to the design of the project plan since the submission of the proposal. Several small changes have been made such as a more accurate team timeline for the competition and more refined processes for STEM outreach have been added.

# 3. Launch Vehicle Summary

This section provides a more in-depth look at the launch vehicle which will be created by the PSP-SL team for the 2020 NASA Student Launch competition.

## 3.1. Launch Vehicle Selection, Design, and Rationale

For the selection of a viable launch vehicle, there are many considerations to be made during the design phase. In any given launch vehicle, these constraints will change many times. For the purposes of this competition, three driving constraints are the size of the payload, whether the price for the vehicle fits into the budget, and the launch vehicle will have a diameter of 6”. For the selection of the launch vehicle, the goal was to keep the stability between 2.7 and 3.2 cal. The objective is to meet the team derived requirements, as well as additional requirements derived by NASA, and to make sure the apogee is not affected dramatically. Selection of the diameter of the launch vehicle was driven by the size of the payload, therefore 6” was decided very early in the project development. For avionics consideration, the weight of the launch vehicle must be around 56lbm to ensure the main parachute can successfully complete its mission. These are a few of the important considerations that went into the design and selection of a launch vehicle for the 2020 competition.

### 3.1.1. Mission Statement and Success Criteria

The mission is to design, build, and fly a fully-reusable, student-built launch vehicle capable of carrying a scientific payload to an altitude of 4325ft AGL. For us to consider the flight a success, the vehicle must:

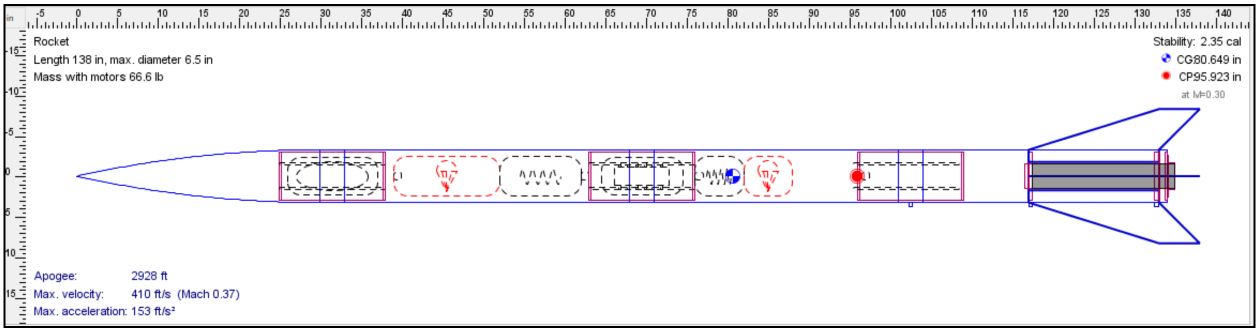
1. Make a stable ascent
2. Fully deploy both the drogue and main recovery systems at the proper altitudes
3. Stay completely tethered and have no free-falling sections
4. Fully deploy the payload after landing
5. Be flyable again without any repairs or alterations

### 3.1.2. Considered Designs and Their Capabilities

In any engineering design process, multiple designs must be considered of which those designs are eventually narrowed down to the one final design. Listed below are some of the considered design alternatives.

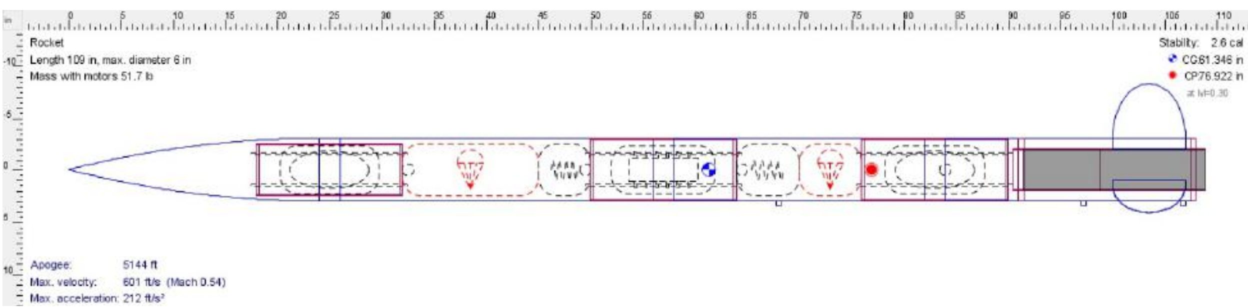
**Considered Design #1:**

One of the considered design was a 6.5” diameter and 138” long launch vehicle. The downsides of this design outweighed the benefits, primarily due to the high weight and low commercial manufacturability of 6.5” airframes. The fin design included four trapezoidal fins with a root chord of 16” and a tip chord of 5”. This, plus the increased length and diameter, made the launch vehicle very heavy at around 66.6lbm. Another consequence of the weight was the predicted apogee. Using the same motor as the ultimately selected design, the predicted apogee was estimated to be 2928ft, far below the NASA requirement for altitude, which results in disqualification: because of this consideration, coupled with the increased weight and decreased stability, the design was determined to be infeasible.



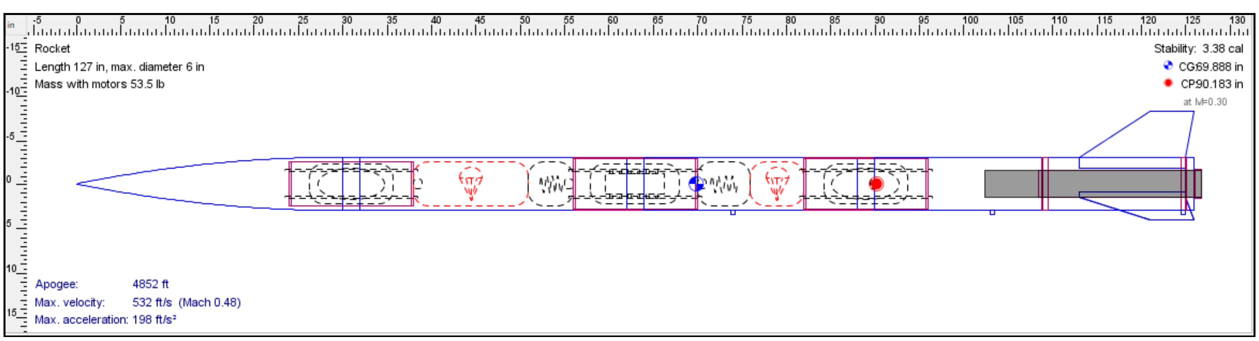

### Considered Design #2:

Another considered design involved a shorter launch vehicle with elliptical fins that was primarily intended to reduce weight on the vehicle. The launch vehicle was 109" long, weighing 51.7lbm, with a 6" diameter and a stability of 2.6 cal. This design was fairly economical, but was not chosen due to several issues: first, elliptical fins were determined to be too difficult to manufacture accurately and smoothly. Additionally, the length of the launch vehicle did not allow adequate space for the payload. Finally, the stability was lower than what was desired, so other designs were favored during selection.




### Considered Design #3:

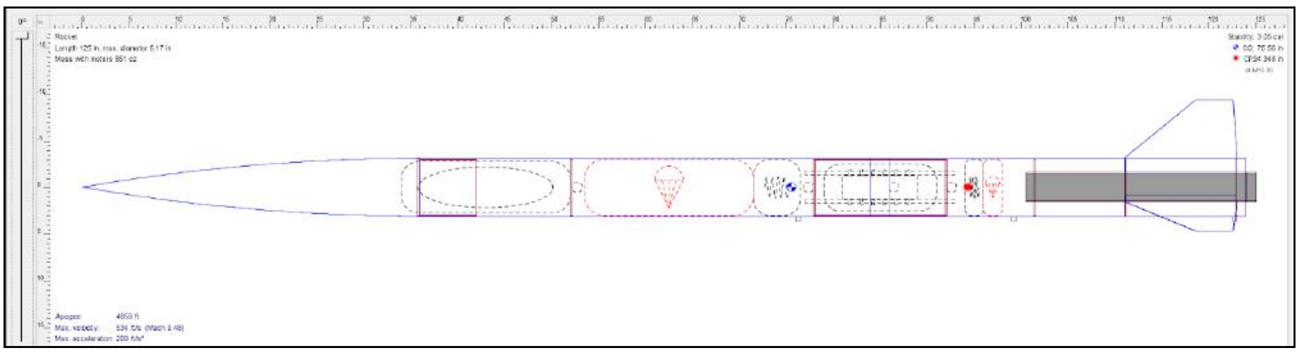
A third considered design was 127" long, included a diameter of 6", weighed 53.5lbm, had a stability of 3.38 calibers, and housed a 75mm motor. This launch vehicle was not only very stable, but in fact overstable: the high stability caused a very large degree of variance of predicted apogee based on wind speed and launch angle cant. It was therefore determined that a launch vehicle with either a higher weight to counter the increased stability, or simply less stability in the first place, would be more ideal for the final launch vehicle design.



**Fin Design:**

Beyond the mentioned designs, the other large variations came from the design of the fins. Considered fin designs (beyond the ones mentioned above) include trapezoidal fins with a root chord of 12", with tip chords varying from 3" to 6.15", varying sweep angle from 30.0-50.5°. Depending on the motor choice and the rest of the predicted mass changes from the OpenRocket launch vehicle models, the fin span (fin height) varied from 6.25" for the 75mm motor to  6.65" for the 98mm motor . The sweep length considered designs also varied from 3.551" to 7.593" for the 75mm motor and from 4.051" to 8.093" for the 98mm  motor. The reason why the fin span and sweep lengths increase for the 98mm motor (compared to the 75mm motor) is because the 98 mm motor is heavier and moves the center of mass towards the bottom of the launch vehicle, which requires the center of pressure to move towards the bottom. To achieve this, the team increases the fin span and the sweep length. All fin designs aim for the desired stability range of 2.7-3.2 cal in order to guarantee stability required (plus a team safety factor) while still not falling into an overstable range.

### 3.1.3. Chosen Design and Subsystems




The chosen design is a 6.17" maximum outer diameter and 6" inner diameter launch vehicle with a length of 125" and a GLOW of 53.2lbm. This chosen launch vehicle's stability is 3.05 cal on the pad.

Regarding the motor, the team has chosen a design that fits a 75mm motor. The main reason behind choosing a 75mm launch vehicle over a 98mm is stability. This design was one of the lightest designs the team had while also allowing the vehicle stability to stay above 2.75 cal. This allows more weight to be allocated to subsystems such as avionics and payload, as well as extra packing space for the main parachute.

The chosen fin design is a trapezoidal shaped fin with a root chord of 12.00", tip chord of 4.00", height of 6.25", sweep length of 7.58" and a sweep angle of 50.5 degrees. The thickness of the fin is 0.1875", and all 3 are estimated to weigh 48.1oz including their fin tabs and 1.5" radius root fillets.

### 3.1.4. Considered Motors and Their Capabilities

Given the initially expected size and weight of the launch vehicle, a high impulse L-class motor would be necessary to generate the appropriate amount of thrust. Motor candidates were narrowed from this broad category by considering cost, size, capabilities, and simulating flights of the previous year's launch vehicle with each potential motor. Several motors deemed potentially acceptable were analyzed in more depth, both in the 75mm and 98mm sizes. At 75mm, the team considered the Cesaroni L1115, Cesaroni L1410, AeroTech L1420, and AeroTech L1365. At 98mm, the AeroTech L1500 and Cesaroni L3150 were analyzed. The advantage of using a 98mm motor would be that 98mm motors have a shorter length than 75mm motors, which allows for a shorter lower airframe and decreased overall weight. 98mm motors, however, concentrate more weight in the lower region of the launch vehicle, decreasing stability. This is the primary reason that a 75mm motor was selected, along with the advantage that 75mm motors are generally cheaper than 98mm motors.

At 75mm, the Cesaroni L1115 has a max thrust of 1713.3N (385.16lbf) and an average thrust of 1119N (251.56lbf). Its burn time is 4.5s and its total weight is 4404g (9.70lbm). The AeroTech L1420 has a max thrust of 1814N (407.80lbf) and an average thrust of 1420N (319.22lbf). Its burn time is 3.2s and its total weight is 4562g (10.05lbm). At 98mm, the AeroTech L1500 has a max thrust of 1752.0N (393.86lbf) and an average thrust of 1500N (337.21lbf). Its burn time is 3.5s and its total weight is 4659g (10.27lbm). The Cesaroni L3150 has a max thrust of 3670.4N (825.13lbf) and an average thrust of 3137.4N (705.31lbf). Its burn time is 1.5s and its total weight is 4731.0g (10.43lbm). The Cesaroni L1115 motor was selected for its high total thrust and overall system impulse compared to the others.

## 3.2. Avionics & Recovery Subsystem

### 3.2.1. Considered Recovery Designs and Their Capabilities

Four different types of altimeters were considered for the recovery subsystem. Two of these altimeters were the Altus Metrum Telemetrum and the Missile Works RRC3+ Sport. Each of these altimeters were also associated with a specified battery: for the Telemetrum, it was a 3.7V LiPo battery, and for the RRC3+ Sport, it was a 9V alkaline battery. These two altimeters were considered due to their reliability and success in past launches performed by the team. Two of the other options considered were the Missile Works RRC2+ and the Eggtimer TRS. All four of these options were ranked in a decision matrix based on their price, minimum and maximum voltage, maximum height, ratio of max height to cost, area, computer type, weight, reviews, and GPS system.

| Altimeter | Cost | Pros | Cons | Corresponding Battery |
|---|---|---|---|---|
| **Missile Works RRC2+** | $45 | Cheap, small, efficient | No GPS or telemetry capabilities | 9V Alkaline |
| **Missile Works RRC3+ Sport** | $90 | Cheap, stores a large amount of flight data, was successfully used last year | Large | 9V Alkaline |
| **Eggtimer TRS** | $140 | Stores a large amount of flight data | Low efficiency, large, heavy | 7.4V LiPo |
| **Altus Metrum Telemetrum** | $300 | Small, efficient, was successfully used last year | Expensive | 3.7V LiPo |

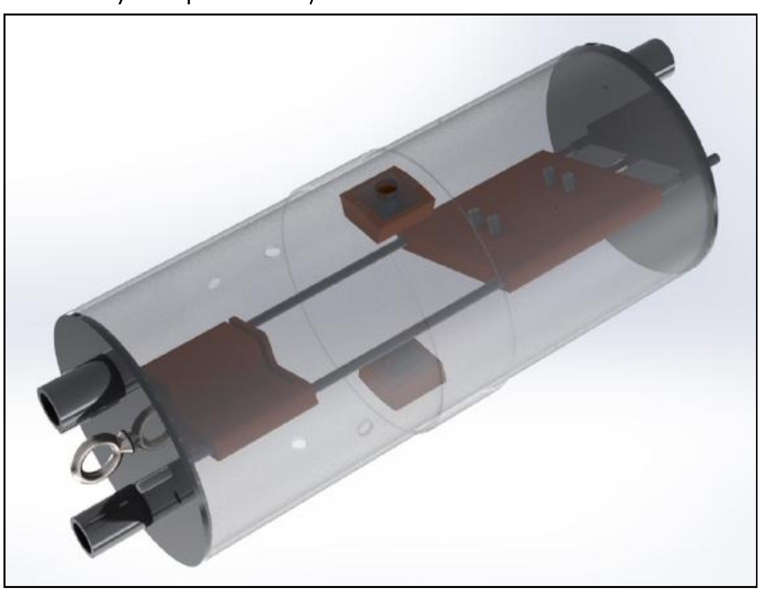
For the ejection charges, a decision matrix was developed to determine whether black powder (FFFFg / 4Fg) or a $CO_2$ ejection device should be used. Several different criteria were used to compare the two options. Some of the more important criteria that were considered include volume, simplicity, reliability, and weight. Beyond this, the cleanliness and style (coolness) had medium to little importance. The estimated values and calculated values were then applied to the decision matrix.

Three main types of switches were researched before making a design decision: button, key, and rocker switches. These specific three were considered due to their relative ease of use and wide-spread prevalence on the market. Button switches were found to be mechanically most simple, but also have the potential of being jostled out of place during flight. However, this risk could be mitigated through the use of a stronger support system and a more robust switch. The key switch was mechanically most complex; requiring a system to turn the key and needing assurance the key would remain in the correct position throughout flight meant this idea was infeasible. Lastly, the rocker switch was found to be mechanically easy to operate and did not compromise the reliability of the circuit.

This year, the team decided to use a switch band as part of the avionics bay. During the launch at Huntsville last year, when the drogue parachute was deployed at apogee, the shear pins in the upper airframe experienced some pressure due to the forces the airframe was experiencing. This resulted in the unintentional deployment of the main parachute shortly after the drogue. To avoid this, the team will be implementing a switch band for both the subscale and full scale launch vehicle to separate the upper and middle airframe.

Choices for bulkhead designs came down to picking between available and purchasable options. Some options included two round plates with holes running through them to hold various attachable objects to the surface of the plate, as well as plates of various metal compositions.

Generally, altimeter sled designs require a surface that slides onto the threaded rods in the avionics bay that is large enough to mount both the Telemetrum and RRC3+ Sport altimeters to but small enough to fit within the dimensions of the coupler. There also need to be battery compartments to hold both the Telemetrum's 900mAh 3.7V LiPo battery and the RRC3+ Sport's 9V alkaline battery, retaining them when the sled is at any angle with respect to the ground. Component configuration options include placing both altimeters on one side of the sled and both batteries on the other and placing one set of altimeters and batteries on either side of the sled and having a space between them lengthwise to place the camera in the avionics bay (since it ideally needs to be located directly underneath the switch band). The first component configuration option would require one more complex 3D printed part, while the second option would require three simpler 3D printed parts (the third being a separate thin piece of material to close off the battery compartments).



Parachute choices were completely reevaluated this year. Eight candidate main parachutes and nine candidate drogue parachutes (all of around the right size for the projected vehicle design) were selected for consideration, including the ones that were used last year. Decision matrices were then developed in order to rank the parachutes from best to worst. Attributes weighted in the decision matrices included size, weight, packing volume, average carrying capacity, drag coefficient, and price. Candidate parachutes were selected from the brands Rocketman, Fruity Chutes, B2, Giant Leap launch Rocketry, Top Flight Recovery, and Dino Chutes.

| Main Parachute | Cost | Pros | Cons |
|---|---|---|---|
| **Rocketman Standard (144")** | $155.00 | Light, high carrying capacity, cheap | Very large, high packing volume, low drag coefficient |
| **Fruity Chutes Iris Ultra Standard (84")** | $296.96 | Small, light, low packing volume, high drag coefficient | Low carrying capacity, expensive |
| **Fruity Chutes Iris Ultra Standard (96")** | $348.15 | High carrying capacity, high drag coefficient | High packing volume, very expensive |
| **SkyAngle Cert-3 XL (100")** | $189.00 | High carrying capacity, high drag coefficient, was successful with it last year | Heavy |
| **SkyAngle Cert-3 XXL (120")** | $239.00 | Very high carrying capacity, high drag coefficient | Large, heavy, expensive |

**Also Considered:** Rocketman Standard (120"), Giant Leap Rocketry TAC-1 (84"), and Top Flight Recovery Crossfire (120")

| Drogue Parachute | Cost | Pros | Cons |
|---|---|---|---|
| **Rocketman Standard (24")** | $28.50 | Light, low packing volume, cheap | Low drag coefficient, low carrying capacity |
| **Rocketman Standard (36")** | $40.50 | Light, low packing volume, high carrying capacity | Large |
| **Fruity Chutes Classic Elliptical (24")** | $64.00 | Light, low packing volume, high drag coefficient | Expensive, moderate carrying capacity |
| **SkyAngle Cert-3 Drogue (24")** | $27.50 | Cheap, was successfully used last year | Heavy, low carrying capacity, low drag coefficient |

**Also Considered:** Rocketman Pro Experimental (24"), Rocketman Pro Experimental (36"), Giant Leap Rocketry TAC-1 (24"), Top Flight Recovery Crossfire (24"), and Dino Chutes Octagon (24")

### 3.2.2. Leading Recovery Design

**General:**

Both the Altus Metrum TeleMetrum and the Missile Works RRC3+ Sport will be used for the recovery subsystem. The TeleMetrum was chosen as the primary altimeter, while the RRC3+ Sport will be the redundant altimeter. These two altimeters were chosen due to their high score on the decision matrix. While the Telemetrum had a higher cost, it had a significantly higher maximum height and smaller area than the other options. Additionally, the Telemetrum contains a GPS and telemetry system which put it over the other options. The RRC3+ Sport was the second highest ranking altimeter due to its cheaper price and its ability to store large amounts of flight data, making it a great alternative altimeter despite its large size. Also, in case of a failure in the primary altimeter, it would be less likely for the same failure to occur to a redundant altimeter of a different make and model.

On the ejection charge type decision matrix, the black powder scored a total of 245 points, whereas the $CO_2$ ejection device received a score of 195. Comparing the two total point values, black powder was the clear choice for the type of ejection charge that should be used. Specifically, black powder was chosen because it occupies less volume, takes less time to develop, and leaves less residue. These advantages outweigh the advantage of the $CO_2$ canister being less heavy. Black powder has also been used in the past, and has been found to be reliable. In terms of design, ejection canister caps in combination with masking tape, aluminum foil, and a section of latex glove will be used to contain the black powder. According to previous calculations, around 4g of black powder will be used for each ejection charge.

The switch design to be used in both the subscale and full scale models will be the rocker switch. This choice represented a middle ground between mechanical complexity and reliability. In addition to these design factors, this is the switch type that has been used on previous projects, and previous experience will help to insure a reliable design. Having this feature in the avionics bay will undoubtedly increase the functionality and reliability of both models. Also, a 3D printed switch holder will be used, with a curve that will conform to the inner diameter of the coupler to ensure a secure fit.
The parachutes that have been selected for this year's design are the 24" Fruity Chutes Classic Elliptical for drogue and the 120" Skyangle Cert-3 XXL for main. The Fruity Chutes drogue parachute was selected because it has a much higher drag coefficient (1.5 - 1.6) and a much lower weight (2.2 oz) than the 24" Skyangle Cert-3 Drogue that was used last year, so it will be much more optimized for this year's design. Generally, it scored very highly in the decision matrix. The Skyangle Cert-3 XXL main parachute was selected, even though it was not originally considered in the decision matrix, because it has a high enough carrying capacity to allow the heaviest section of the launch vehicle to land with a kinetic energy of less than 75 ft-lbf, as specified in the NASA requirements. Originally, the Skyangle Cert-3 XL was chosen for the main parachute because it was the top scorer in the decision matrix and it has proven to be successful in past launches. Sizing up from the XL to the XXL allows for the beneficial properties of this series of parachutes to be maintained while making sure the one that will be used is large enough for the vehicle's needs.

**Full Scale Specific:**
A coupler that is 14" long will slide between the upper and mid airframe sections. It will have an outer diameter of 5.998" and an inner diameter of 5.775". Additionally, the switch band will have an outer diameter of 6.17", an inner diameter of 6", and a length of 2". The switch band is primarily used to separate the upper and middle airframe so that they can function as two separate entities during launch and deployment.

The leading bulkhead design features a circular plate with varying diameters. The larger disk has a diameter of 5.998", while the smaller disk has a diameter of 5.775". The thickness of each respective plate is 0.125". This is to make the bulkhead fit perfectly in the coupler. The bulkhead has one hole in the middle to fit an I-bolt, and also has two holes centered on either side to which the threaded rods will secure. Two terminal blocks and two black powder canisters will also be fastened to the plate.

The leading full scale altimeter sled design is a rectangular prism with rounded edges and holes to slide onto the threaded rods in the avionics bay. It will also contain eight holes for mounting the various altimeter posts required for the two altimeters. The sled will be 4.5" long, 4.55" wide, and 0.55" thick. It was decided that it would be best to separate the battery compartment and place it on the other end of the bay, allowing for the camera to be located in between the two sections. This is to ensure that the mass distribution within the avionics bay is as even as possible. The battery compartment will be 2.25" long, 4.55" wide, and 1.71" thick to accommodate the various sizes of the batteries.

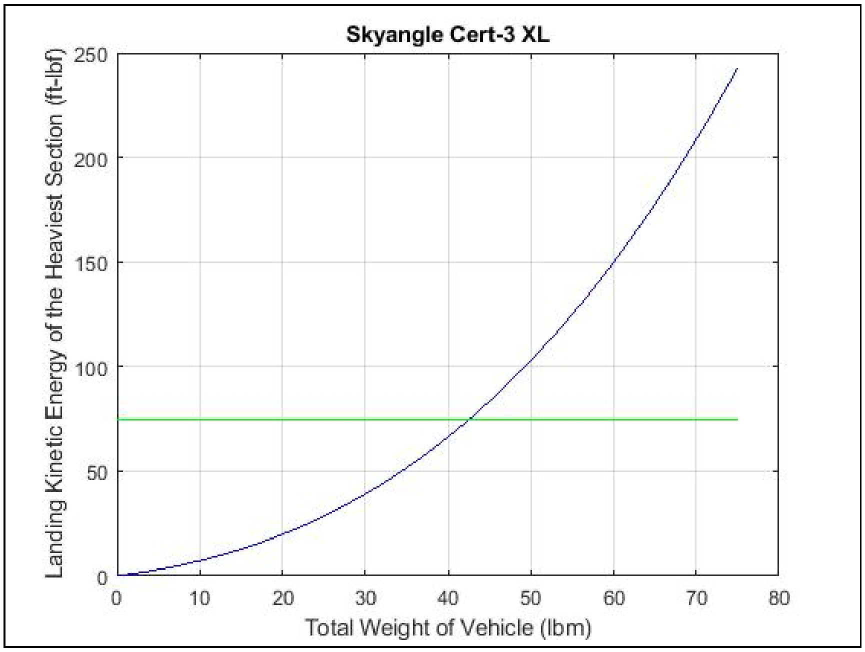
**Subscale Specific:**
A coupler that is 6" long will slide between the upper and mid airframe sections. It will have an outer diameter of 2.998" and an inner diameter of 2.875". Additionally, the switch band will have an outer diameter of 3.125", an inner diameter of 3", and a length of 1".

The leading bulkhead design features a circular plate with varying diameters. The larger disk has a diameter of 2.998", while the smaller disk has a diameter of 2.875". The thickness of each respective plate is 0.125". The bulkhead has one hole in the middle to fit an I-bolt, and it also has two holes centered on either side to which the threaded rods will secure.

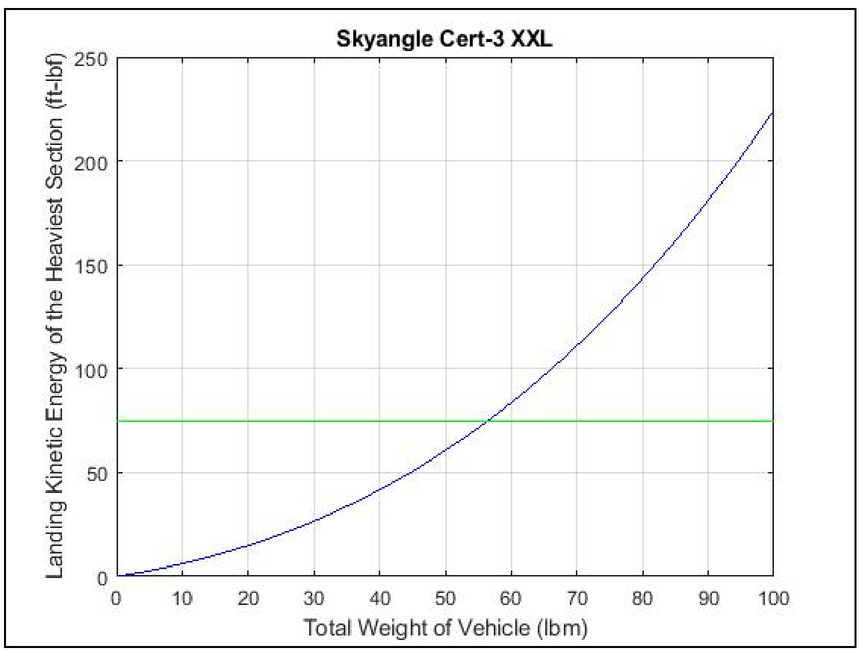
The leading subscale altimeter sled design will be similar to the full scale one, but the altimeter sled and the battery compartment will be together in one 3D printed piece rather than separated. This is because there will not be a camera implemented in the subscale vehicle, which would require this separation. Also, the altimeter sled will only hold the RRC3+ Sport altimeter for altitude recording purposes, as motor ejection will control deployment for the subscale vehicle. The dimensions for the subscale altimeter sled have not yet been defined. A JollyLogic Altimeter One will also be attached to provide redundancy, this also allows us to not use the TeleMetrum, and potentially have an issue later on in competition in regards to budget.

### 3.2.3. Preliminary Parachute Sizing Analysis

For sizing the drogue parachute, it was determined that a parachute with the same diameter as the one from last year but with a drag coefficient of about 50% greater would be sufficient for the current design. Therefore, a 24" Fruity Chutes Classic Elliptical parachute was chosen to be the drogue parachute. For sizing the main parachute, initially the parachute from last year was chosen (Skyangle Cert-3 XL), but concerns began to arise (as the total weight of the launch vehicle was solidified) that its heaviest section would land with a kinetic energy higher than that specified in the NASA requirements. Therefore, MATLAB code was written to determine the maximum starting weight of the launch vehicle in order for the heaviest section to land with a kinetic energy of less than 75ft-lbf, assuming that it accounts for 31% of the total weight of the vehicle.



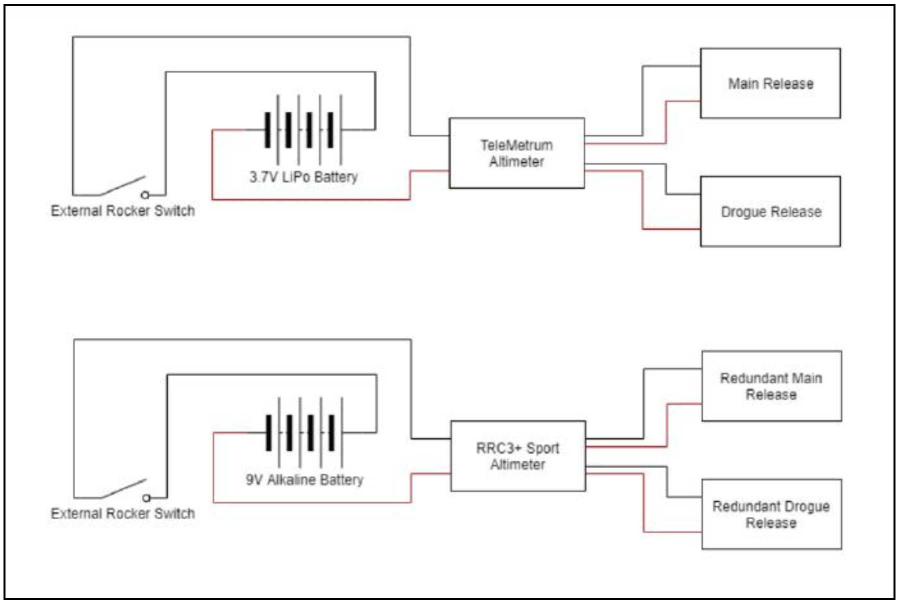

**Plot for the Skyangle Cert-3 XL Parachute**




**Plot for the Skyangle Cert-3 XXL Parachute**

The intersection of the blue and green lines in the plots represents the total weight of the vehicle that would result in a landing kinetic energy of 75 ft-lbf for the heaviest section. Therefore, this represents the maximum starting weight. With the original parachute choice (Skyangle Cert-3 XL), the maximum starting weight would be 43lbm. With a parachute one size larger that is already in the team's possession (Skyangle Cert-3 XXL), the maximum starting weight would be 56.5lbm. Since the current projected total weight of the launch vehicle is about 55.6lbm, the Skyangle Cert-3 XL would no longer be sufficient as the main parachute. However, the Skyangle Cert-3 XXL would provide a low enough landing kinetic energy for the heaviest section of the launch vehicle. Therefore, the choice was made to switch to the Skyangle Cert-3 XXL as the main parachute in the launch vehicle design.

#### 3.2.4. Proof of Recovery Redundancy




**Avionics Wiring Diagram**

The wiring diagram above features two nearly identical systems, both of which serve the same purpose. Both of these systems intend to direct the sequential release of the main and drogue parachute, but the second system will only be necessary if the first system fails. The main difference between the two revolves around the different altimeters and batteries. The different altimeters and batteries are meant to prevent any repeated malfunctions within the measuring devices: if one system fails for a particular reason, the other device in the redundant wiring diagram is less likely to fail for the same reason.

### 3.3. Mission Performance Predictions

#### 3.3.1. Official Target Altitude

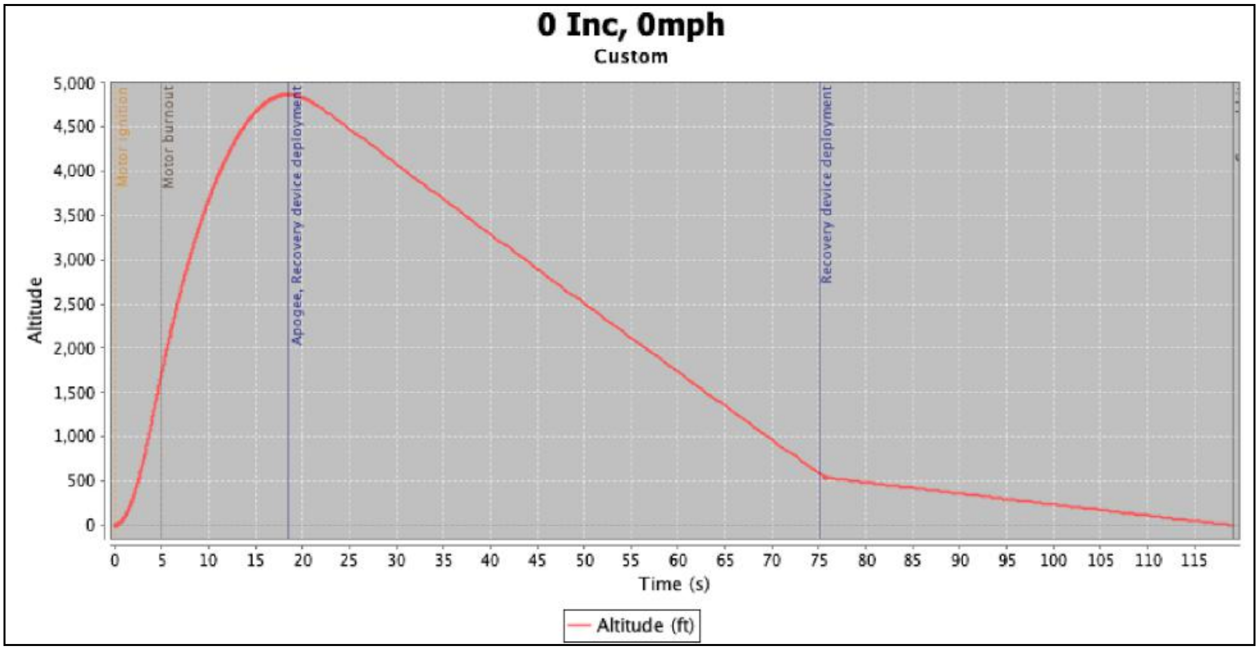
The team's official launch day target altitude will be 4325ft AGL per the tables and justifications which follow. This altitude was chosen through a series of OpenRocket simulations which used 0-20mph wind speeds and 0-15° launch rail cant conditions and accounting for a small range of mass growth. Conditions which are most expected during launch week were assigned heavier weights and an average of averages was determined. Simulations were conducted using the conditions of Bragg Farms in Huntsville, AL, the location of the final launch. Those conditions are: Latitude 34.7 N, Longitude 86.6 W, altitude above sea level of 650 ft, average temperature of 77 °F, and a launch rod of twelve feet.
The tables below show an overall system average apogee of 4329.375ft. The team knows that there will be a percent error with this, keeping in mind that the Runge-Kutta scheme OpenRocket uses tends to have a variation of around 50ft; however, the team believes this error to be acceptably low.

| Percent Likelihood [%] | Test Case | | Theoretical Apogee [ft] | | | | Test Case Altitude Averages [ft] |
|---|---|---|---|---|---|---|---|
| | Launch Angle [deg] | Pad Wind Speed [mph] | +0lbm Mass Margin | +1.5lbm Mass Margin | +2lbm Mass Margin | +3lbm Mass Margin | |
| 10 (Ideal) | 0 | 0 | 4867 | 4670 | 4606 | 4479 | 4655.5 |
| 30 (Less Realistic) | 5 | 5 | 4744 | 4555 | 4494 | 4367 | 4540 |
| 40 (Reasonably Realistic) | 5 | 10 | 4647 | 4481 | 4416 | 4295 | 4459.75 |
| 40 (Reasonably Realistic) | 10 | 5 | 4542 | 4358 | 4299 | 4180 | 4344.75 |
| 60 (Significantly More Realistic) | 10 | 10 | 4431 | 4237 | 4190 | 4073 | 4232.75 |
| 5 (Worst Case) | 15 | 20 | 3844 | 3662 | 3596 | 3479 | 3645.25 |
| Altitude Weighted Averages | | | 4540 | 4358.66 | 4301.66 | 4182.66 | |

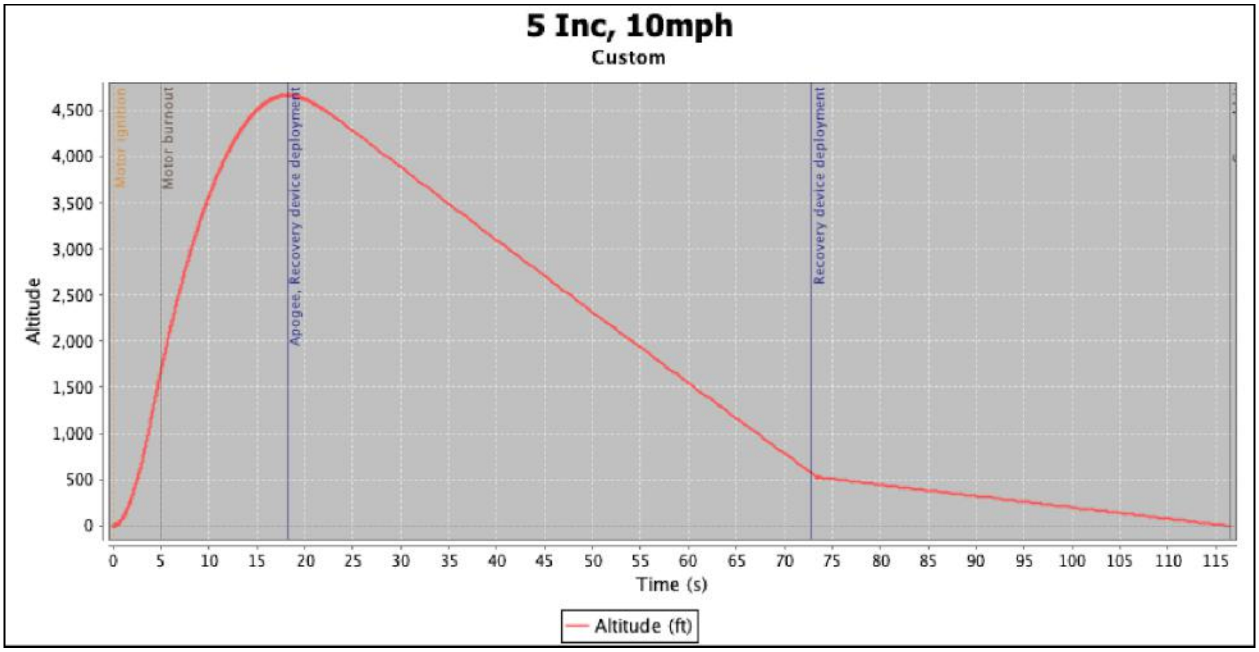
| | Averages Across All Test Cases [ft] | Averages Across All Mass Margins [ft] |
|---|---|---|
| | 4655.5 | 4540 |
| | 4540 | 4358.66 |
| | 4459.75 | 4301.66 |
| | 4344.75 | 4182.66 |
| | 4232.75 | - |
| | 3645.25 | - |
| Average of Averages [ft] | 4313 | 4345.75 |
| Overall System Average [ft] | 4329.375 | |

### 3.3.2. Flight Profile Simulations and Altitude Predictions

In the 2019 competition, a large amount of consideration was given towards varying wind speeds. However, the team failed to incorporate launch rail inclination into their simulation data. In this year's competition, the team gave more consideration to launch rail inclination while deciding to spend less time on the in-depth discussion of each wind case. Instead, there are two in-depth cases described while the other cases are tabulated for ease of understanding. The first case is the ideal case of no wind and no rail inclination. Obviously, this is not feasible, but it gives the perfect performance of the team's launch vehicle. Following that case is a 10mph average wind speed case with 5 degrees of launch rail inclination. Looking up average wind speed in early April in Huntsville, AL, the expected winds should be between 7 and 9 mph. Using a slightly higher speed should give the team more room for error. In addition, the rail is likely to be inclined away from the spectators, so the team decided that 5 degrees is the most likely case.




**Altitude vs Time for a Case with Zero Wind (above)**



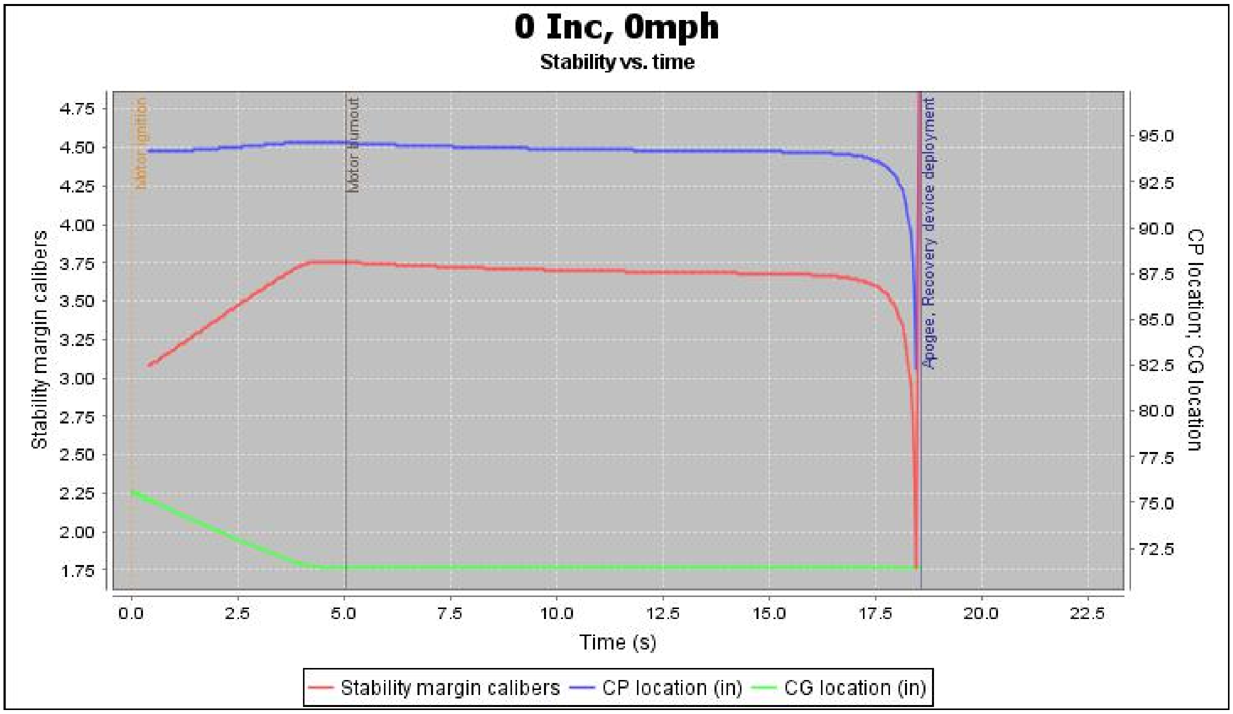

**Altitude Vs Time for a Case with 10 mph wind at 5 degrees**

As can be seen from the graph above, the launch vehicle is simulated to reach a maximum altitude of 4,669 feet above ground level. This is 344 feet above the target altitude. At this time, the team is assuming that there is 10 mph wind and the launch vehicle will be launched at a 5 degree inclination. The team is continuing to run multiple scenarios with different speeds and different inclinations. The team is currently deliberately incorporating this excess altitude due to the fact that the team do not currently have a physical model on which to base the computer simulations. Once the team has constructed the flight vehicle, a more accurate weight measurement for the launch vehicle that can then be entered into the simulation program. Because the launch vehicle is anticipated to weigh more than the simulation shows, as weight is added into the computer model the altitude will decrease. From previous years of construction of the physical launch vehicle, the adhesive used for the fins adds measurable weight to the launch vehicle which the team is also anticipating and attempting to record using a subscale model as well as during full scale launch tests.

Other factors, such as surface finish and the cross sectional airfoil of the fins, are variables that the team does not have implicit control over. The team cannot accurately measure surface smoothness to compare the real and digital models, which will account for some difference in the actual and expected altitudes. In addition, the only choices presented to us by OpenRocket when varying the cross section of the fins are “square, rounded, or airfoiled”. There is no direct input for edge thickness or taper length, further limiting the simulations. Although these simulations provide data that may not be exact, they provide insight into obtaining a baseline performance which can then be used for future improvements.

All altitude simulations from which the graph above is derived were accomplished using OpenRocket 15.03 using the extended Barrowman calculation method and a six-degree-of-freedom Runge-Kutta 4 simulation method. Geodetic calculations were evaluated using spherical approximation, and a 0.02 second time step for simulation calculations was used. Further altitude calculations will be done in RASAero II using similar parameters, and will be discussed later.

### 3.3.3. Center of Pressure, Center of Gravity, and Stability




**Graph Of CP, CG, And Stability Vs. Time for the Zero Wind Case**

As seen from the graph above, the launch vehicle case exits the 144" launch rail with a minimum stability margin of 3.08 cal, meeting the minimum requirement of two calibers. During the ascent phase, the launch vehicle does not experience a significant drop in stability until it reaches a low enough velocity that the fins cannot maintain aerodynamic stability. At this point, the launch vehicle begins slowing down significantly due to drag and gravity and starts arcing over as it approaches apogee. Despite this, the launch vehicle maintains above 3.5 cal for nearly all of the boost and coast phase.

The center of pressure, the node where the total sum of all pressures acts on the vehicle, starts at a distance of 94.154 inches from the datum, which is deemed to be the tip of the nose cone. The center of gravity, a node where all moments about an axis of rotation equally oppose each other, begins at a distance of 75.560 inches from the datum of the launch vehicle, placing it 18.594 inches ahead of the center of pressure. During the burn time of the motor, the center of gravity moves forward at a constant rate due to the constant burn rate of the solid propellant. The total shift is 4.101 inches, or almost one full caliber.

### 3.3.4. Kinetic Energy Calculations

**Velocity and Weight Values**

$$Terminal\ velocity\ under\ drogue\ parachute\ =\ 98.4\ ft/s$$
$$Landing\ velocity\ under\ main\ parachute\ = 12.4\ ft/s$$

$$Weight\ of\ upper\ section\ = 22.7\ lbm\ = 0.706\ slugs\ (mass)$$
$$Weight\ of\ middle\ section\ (avionics\ bay)\ = 6.3\ lbm\ =\ 0.196\ slugs\ (mass)$$
$$Weight\ of\ lower\ section\ = 13.3\ lbm\ = 0.413\ slugs\ (mass)$$

**Drogue**

$$Kinetic\ energy\ of\ upper\ section\ =\ \frac{1}{2} * 0.706\ slugs\ *\ (98.4\ ft/s)^2 = 3416.8\ ft\ lbf$$

$$Kinetic\ energy\ of\ middle\ section\ (avionics\ bay) =\ \frac{1}{2} * 0.196\ slugs\ *\ (98.4\ ft/s)^2 = 948\ ft\ lbf$$

$$Kinetic\ energy\ of\ lower\ section\ =\ \frac{1}{2} * 0.413\ slugs\ *\ (98.4\ ft/s)^2 = 1999.4\ ft\ lbf$$

$$Total\ kinetic\ energy\ =\ 3416.8\ ft\ lbf + 948\ ft\ lbf + 1999.4\ ft\ lbf = 6364.2\ ft\ lbf$$

**Main**

$$Kinetic\ energy\ of\ upper\ section\ =\ \frac{1}{2} * 0.706\ slugs\ *\ (12.4\ ft/s)^2 = 54.3\ ft\ lbf$$

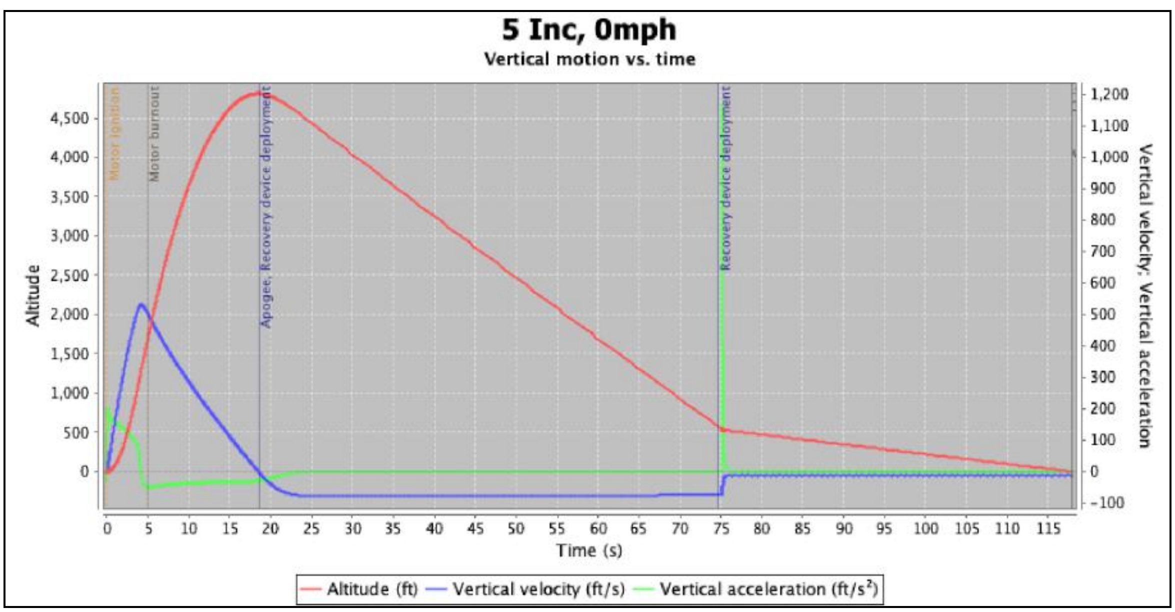
$$Kinetic\ energy\ of\ middle\ section\ (avionics\ bay) =\ \frac{1}{2} * 0.196\ slugs\ *\ (12.4\ ft/s)^2 = 15.1\ ft\ lbf$$

$$Kinetic\ energy\ of\ lower\ section\ =\ \frac{1}{2} * 0.413\ slugs\ *\ (12.4\ ft/s)^2 = 31.8\ ft\ lbf$$

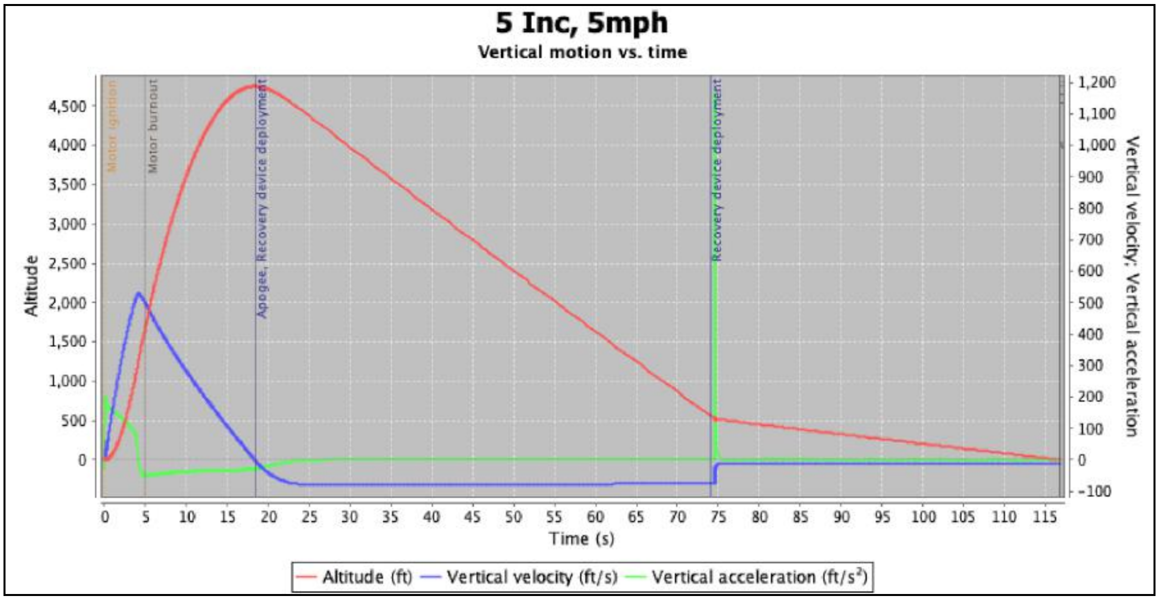
$$Total\ kinetic\ energy\ =\ 54.3\ ft\ lbf + 15.1\ ft\ lbf + 31.8\ ft\ lbf = 101.2\ ft\ lbf$$

### 3.3.5. Descent Time Calculations

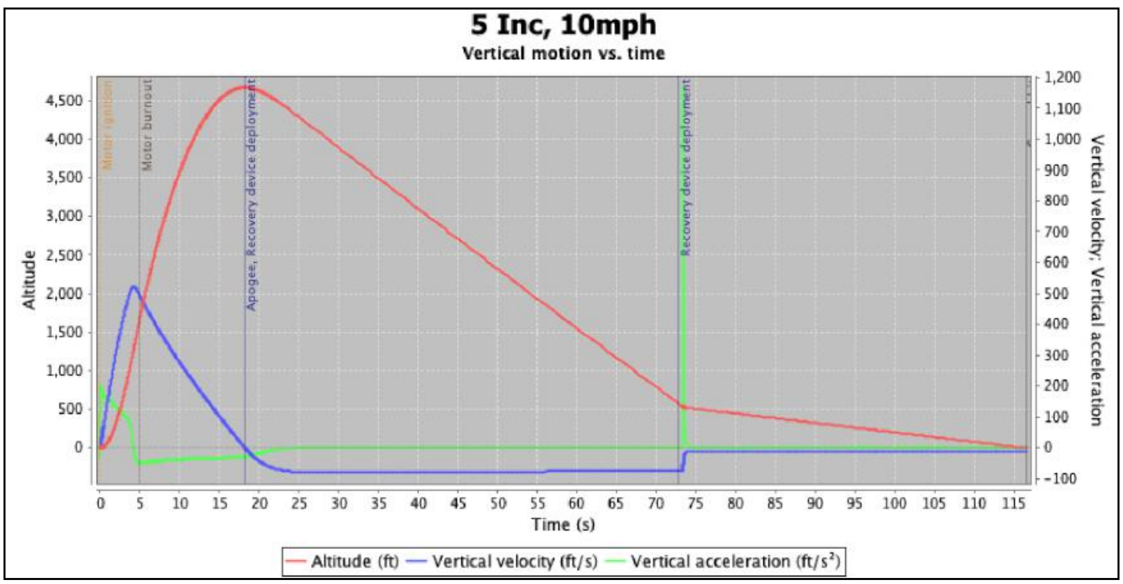
Assuming a five degree cant on the launch rail during launch day, if there is zero or minimal winds, the descent time according to OpenRocket is 92.1 seconds with the main parachute deploying at 49.1 seconds after apogee. If winds are at five miles per hour during launch day, the descent time according to OpenRocket is 93.2 seconds with the main parachute deploying at 49.2 seconds after apogee. With ten mile per hour winds, the descent time according to OpenRocket is 91.4 seconds with the main parachute deploying at 48.4 seconds after apogee. When winds are at fifteen miles per hour, the descent time according to OpenRocket is 90.7 seconds with the main parachute deploying at 48.7 seconds after apogee. At twenty miles per hour winds, the descent time according to OpenRocket is 88.8 seconds with the main parachute deploying at 49.8 seconds after apogee. The descent times assuming a five degree cant can be seen in the vertical motion versus time graphs below. The descent of the vehicle begins at the first blue vertical line and ends at the right-hand side of the graph. The team expects these values to decrease to under 90 seconds, as the targeted apogee predicts an increase in vehicle mass of up to 3lbm.



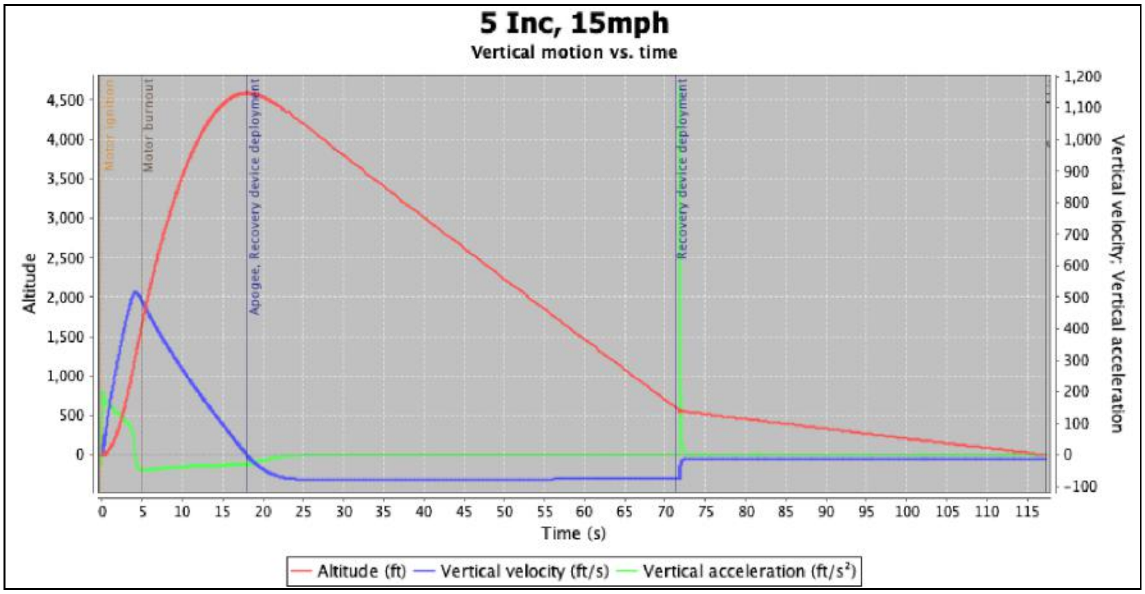

**Altitude, Vertical Velocity and Vertical Acceleration over Time for a Launch Rail Canted at 5 Degrees with 0 Miles Per Hour of Wind**



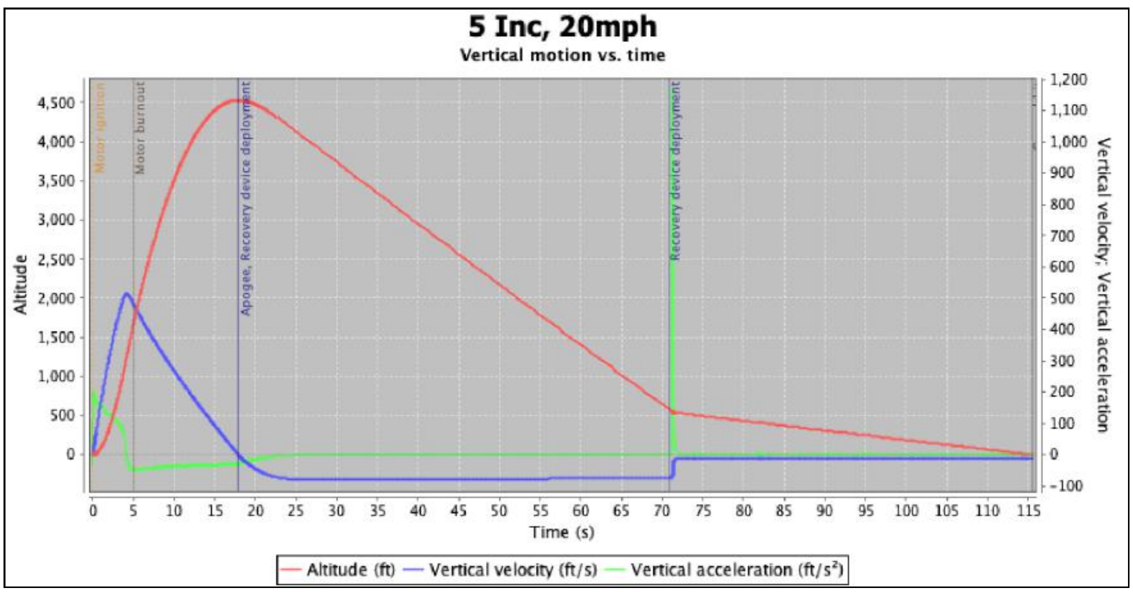

**Altitude, Vertical Velocity and Vertical Acceleration over Time for a Launch Rail Canted at 5 Degrees with 5 Miles Per Hour of Wind**




**Altitude, Vertical Velocity and Vertical Acceleration over Time for a Launch Rail Canted at 5 Degrees with 10 Miles Per Hour of Wind**




**Altitude, Vertical Velocity and Vertical Acceleration over Time for a Launch Rail Canted at 5 Degrees with 15 Miles Per Hour of Wind**

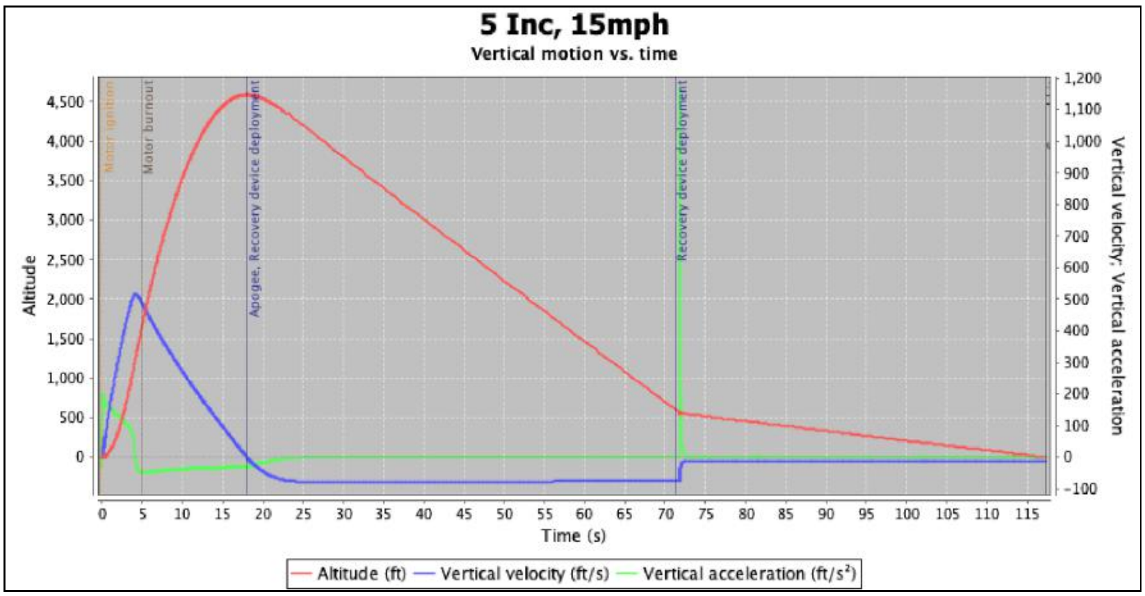



**Altitude, Vertical Velocity and Vertical Acceleration over Time for a Launch Rail Canted at 5 Degrees with 20 Miles Per Hour of Wind**

### 3.3.6. Drift Distance Calculations

To calculate drift distance, the team used the equation stating drift distance equals the vehicle's descent time multiplied by the wind speed. This equation assumes that the wind blows in only one primary direction during descent. Other assumptions made in this equation are that the launch rail at launch day is canted at five degrees during launch and that the apogee is directly above the launch point. The 20mph case is over the allowed 2500ft drift distance of the competition, but the team also recognizes that the chance it is both allowed to launch in 20 mph winds is low, and the distance is under 2500ft for 19mph wind speeds.

| Launch Angle [deg] | Wind Speed [mph] | Drift Distance From Pad [ft] |
|---|---|---|
| 5 | 0 | ~0 |
| 5 | 5 | 684 |
| 5 | 10 | 1340 |
| 5 | 15 | 1995 |
| 5 | 20 | 2605 |




### 3.3.7. Verification of Mission Performance Predictions

The team used RASAero II as a means to verify its mission performance predictions from OpenRocket. In order to simulate the conditions at Bragg Farms during launch day in early April, the team inputted 650' as the simulated launch field elevation, 30.0mmHg as the launch field air pressure, 74°F as the launch temperature, and 12' for the launch rail. The data below shows the flight results in accordance to varying wind speeds from 0-20mph and varying launch rail inclinations from 0-15°. The simulation for 0° inclination and 0mph wind speeds is the ideal case and is about 130' above the predicted altitude obtained from OpenRocket. For the simulations of 5-10mph wind speeds, the predicted altitude ranges from 3621' to 4316'. For the simulation of 10mph wind speeds with a 5° rail inclination, which the team has predicted to be most realistic for launch day, the predicted apogee is 4074 ft, which is about 175-200 ft below the results from a similar simulation in OpenRocket. Each of these predicted altitudes has a certain percentage of error compared to OpenRocket, but the team believes it to be small enough to verify the OpenRocket results.

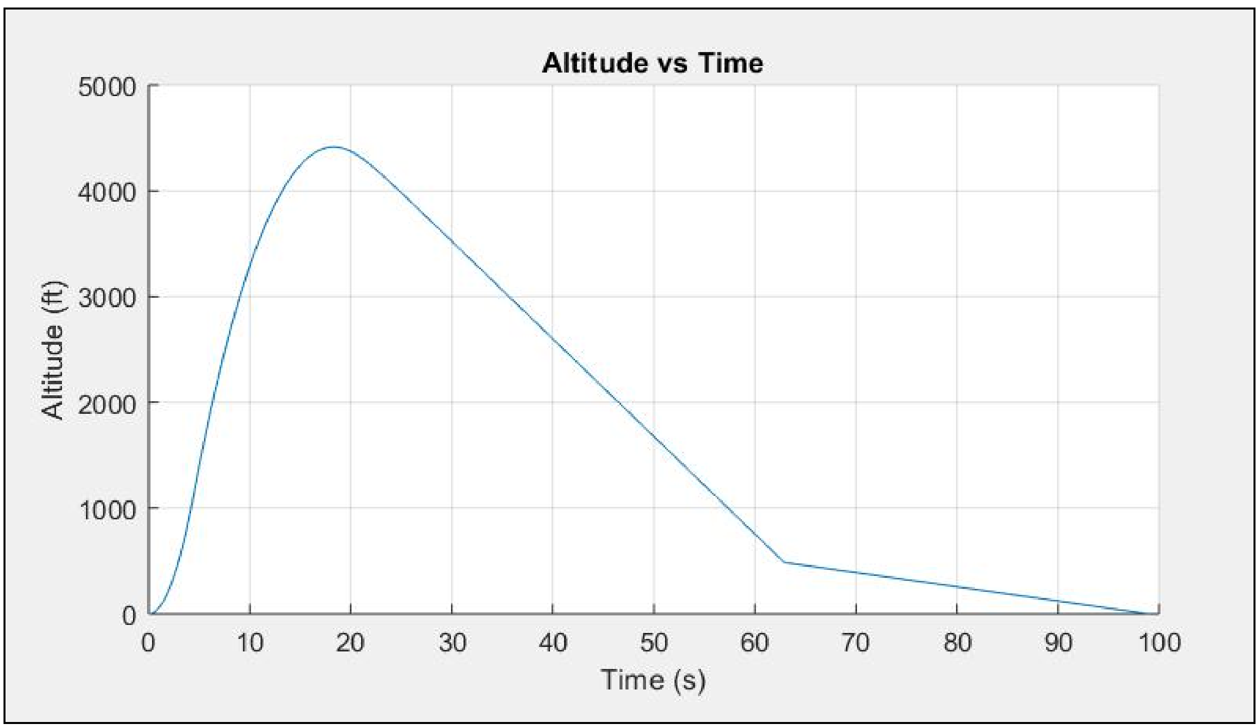
| Design 1 (10/29/2019) | | | | |
|---|---|---|---|---|
| Test | Simulation Settings (Launch Rail 12 ft) | | Simulation Results | |
| | Launch Angle [deg] | Wind Speed [mph] | Apogee [ft] | Max Velocity [ft/sec] |
| 1 | 0 | 0 | 4867 | 535 |
| 2 | 0 | 5 | 4855 | 535 |
| 3 | 0 | 10 | 4821 | 534 |
| 4 | 0 | 15 | 4746 | 533 |
| 5 | 0 | 20 | 4667 | 531 |
| 6 | 5 | 0 | 4811 | 536 |
| 7 | 5 | 5 | 4751 | 535 |
| 8 | 5 | 10 | 4669 | 535 |
| 9 | 5 | 15 | 4589 | 535 |
| 10 | 5 | 20 | 4533 | 534 |
| 11 | 10 | 0 | 4642 | 538 |
| 12 | 10 | 5 | 4534 | 538 |
| 13 | 10 | 10 | 4415 | 538 |
| 14 | 10 | 15 | 4273 | 537 |
| 15 | 10 | 20 | 4172 | 536 |
| 16 | 15 | 0 | 4373 | 541 |
| 17 | 15 | 5 | 4243 | 541 |
| 18 | 15 | 10 | 4092 | 541 |
| 19 | 15 | 15 | 3937 | 540 |
| 20 | 15 | 20 | 3828 | 540 |

### 3.3.8. Recovery Mission Performance Verification

The following MATLAB simulation of the trajectory of the launch vehicle serves as verification for the actual launch in addition to using RASAero II. It plots the altitude vs range and the altitude vs time. The altitude vs range plot gives the estimated flight path and allows easy modification to the specifications to alter flight path. The code takes into account some estimated wind speeds, the atmospheric pressure at launch, and air density at launch. In order to verify the accuracy of the code, the previous launch vehicle specifications and experimental data were used.

The code was divided into 4 phases, the boost phase, coast phase, parachute 1 phase, and parachute 2 phase. All the calculations account for drag that the launch vehicle experiences, variation of air pressure, variation of gravity, and estimated wind speed.

1. In the boost phase, basic kinematic equations were used to find the acceleration, velocity, and vertical distance at each time step. For each time step, the drag was calculated first. Next, the acceleration was calculated, taking into account the drag force, thrust force, the force due to gravity, and the changing gross mass of the launch vehicle. The acceleration of the launch vehicle was used to calculate the velocity. Finally, the altitude was found using the acceleration and velocity. This process was repeated until the burn time of the motor was complete. The end of the boost phase is indicated when the mass of the launch vehicle was equal to the dry mass of launch vehicle.
2. In the coast phase, the same equations were used as the boost phase, except the thrust was zero, and the mass used was constant, which was the mass of the launch vehicle with no fuel. The end of the coast phase was indicated by when the velocity of the launch vehicle hit zero.
3. In the parachute 1 phase, the drag produced by the drogue parachute was also taken into account. The end of this phase was indicated when the launch vehicle reached a certain altitude.
4. In the parachute 2 phase, the drag produced by the main parachute was taken into account as well. The end of this phase was indicated when the launch vehicle reached the ground.




**Plot of Altitude vs Time**

### 3.3.9. OpenRocket Launch Vehicle Simulation Data for Various Wind Speed Cases

The following table provides the results the team took from its OpenRocket simulations. The launch site used was Bragg Farms in Huntsville, AL (Starting sea level: 600') (Lat: 34.9 N Long: -86.6 E).

| PDR Final Design (10/29/2019) | | | | | |
|---|---|---|---|---|---|
| Test | Simulation Settings (Launch Rail 12 ft) | | Simulation Results | | |
| | Launch Angle [deg] | Wind Speed [mph] | Apogee [ft] | Landing Velocity [ft/s] | Rail Exit Velocity [ft/s] |
| 1 | 0 | 0 | 4867 | 11.6 | 66.1 |
| 2 | 0 | 5 | 4855 | 11.6 | 66.1 |
| 3 | 0 | 10 | 4821 | 12.5 | 66.1 |
| 4 | 0 | 15 | 4746 | 12,7 | 66.1 |
| 5 | 0 | 20 | 4667 | 12.2 | 66.1 |
| 6 | 5 | 0 | 4811 | 11.6 | 66.2 |
| 7 | 5 | 5 | 4751 | 13 | 66.2 |
| 8 | 5 | 10 | 4669 | 12.1 | 66.1 |
| 9 | 5 | 15 | 4589 | 12.5 | 66.1 |
| 10 | 5 | 20 | 4533 | 12 | 66.1 |
| 11 | 10 | 0 | 4642 | 13.3 | 66.3 |
| 12 | 10 | 5 | 4534 | 13 | 66.3 |
| 13 | 10 | 10 | 4415 | 13 | 66.3 |
| 14 | 10 | 15 | 4273 | 12 | 66.3 |
| 15 | 10 | 20 | 4172 | 13 | 66.3 |
| 16 | 15 | 0 | 4373 | 13.3 | 66.5 |
| 17 | 15 | 5 | 4243 | 11.3 | 66.5 |
| 18 | 15 | 10 | 4092 | 12.3 | 66.5 |
| 19 | 15 | 15 | 3937 | 12 | 66.5 |
| 20 | 15 | 20 | 3828 | 12.4 | 66.5 |

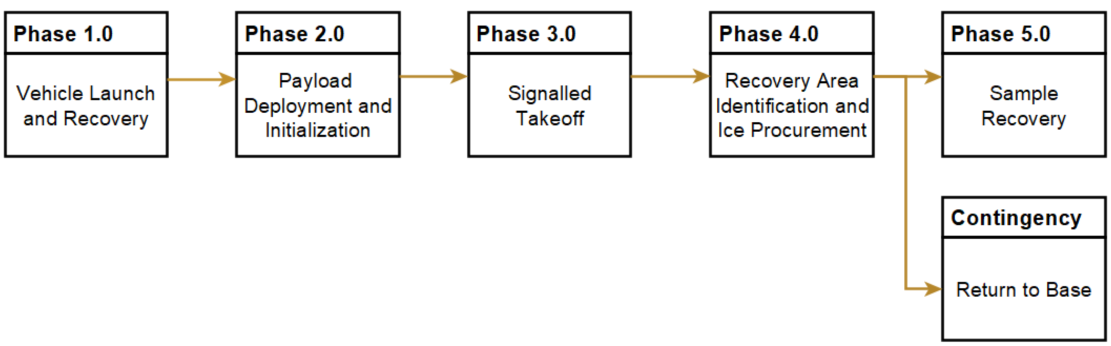
# 4. Payload Criteria

## 4.1. UAS Mission Statement and Overview

The mission of the UAS is to safely identify, extract, and finally recover a simulated lunar ice-sample after UAV deployment from a high-powered launch vehicle post completion of the recovery phase. The UAV will be mechanically retained in the payload bay during flight in a fail-safe retention and deployment (R&D) system. The UAV will be capable of fully autonomous ice recovery. Any and all phases of the mission will have pre-programmed contingencies along with the option of immediate manual override and mission termination.

### 4.1.1. Mission Decomposition and Success Criteria

The mission is divided into five distinct phases with each phase decomposed into functional events that describe the operational mission path along with alternative (contingency) mission paths. The five phases are Vehicle Launch and Recovery, UAV Deployment and Integration, Signaled Takeoff, Recovery Area Search and Ice Procurement, and finally Sample Recovery. The mission and phases will be decomposed into a series of functional flow block diagrams. This also includes contingency planning in the case the autonomous mission planner reaches the necessary criteria to terminate the mission. In order for the UAS to successfully complete its mission, it must complete all functions and phases detailed below.

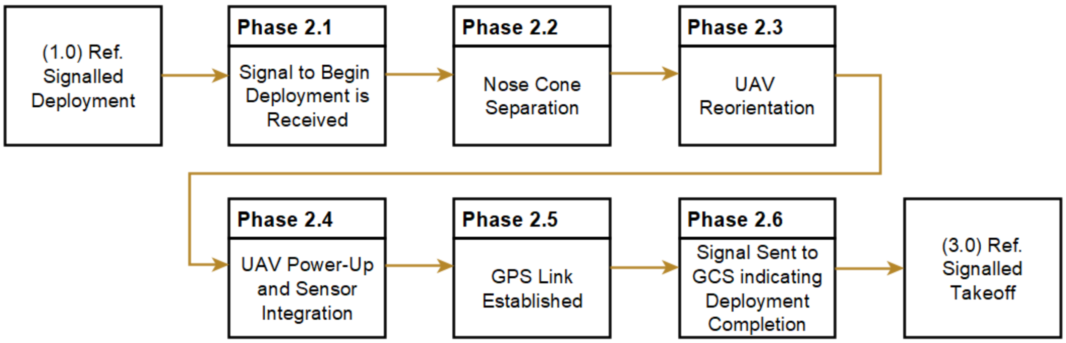



**Phase 1: Vehicle Launch and Recovery**

The vehicle launch and recovery phase will include limited action from the UAS. The UAV will not be turned on to meet requirements set forth by the FAA, and therefore the GCS will not need to be active nor controlled by an operator. Instead, the R&D payload retention system will mechanically hold the UAV through a failsafe mechanism. Upon successful launch, vehicle touchdown, and permission from the RSO, the mission may proceed to Phase 2.

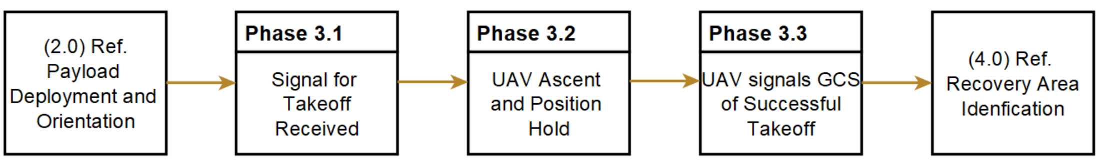
**Phase 2: UAV Deployment and Integration**

Subsequent to the vehicle recovery, the GCS will send a signal to the R&D system to begin the deployment of the UAV from the launch vehicle body. The R&D system will separate the nose cone from the upper airframe of the launch vehicle, exposing an opening in which the UAV will be held on to a sled. Once fully deployed, the UAV will correct its orientation by rotating along the axis of the launch vehicle body. Following the successful deployment and orientation of the UAV, a switch will engage allowing the UAV to be powered. Once powered, the UAV will begin integrating all of its components and await a successful GPS link. Upon obtaining a valid GPS link and successfully integrating all components on the UAV, the mission may proceed to Phase 3. A functional flow diagram describing Phase 2 of the mission is seen in the figure below.



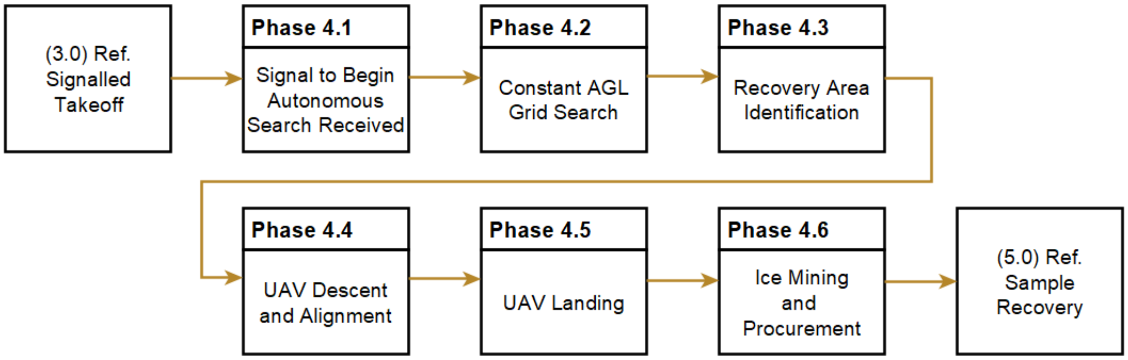

## Phase 3: Signalled Takeoff

The objective of the signalled takeoff phase of the mission is to safely lift the UAV out of the payload bay, placing the vehicle in a position to begin its search for an ice recovery area. The signalled takeoff phase will begin with a signal sent from the UAV to the GCS, informing the ground support team that it has obtained a valid GPS link and has integrated all of its components. The ground support team will then send a signal from the GCS to the UAV, activating the UAV's takeoff sequence. The flight control computer (FCC) will control the takeoff, lifting the vehicle out of the payload bay approximately 100 feet above ground level. Once the UAV has stabilized at this position, the mission may proceed to Phase 4. A functional flow diagram describing Phase 3 of the mission is seen in the figure below.




## Phase 4: Recovery Area Identification and Ice Procurement

After the completion of Phase 3 of the mission, the UAV will begin its search for an ice mining recovery area. This search will occur autonomously, employing a constant-altitude grid search strategy. The UAV will utilize a pre-programmed map of the recovery field with approximate GPS data of the recovery areas to establish its position in 3D space and follow a grid-like trajectory to search for a recovery area near its approximate position. Throughout this process, the UAV's vision system will capture and process images of the ground beneath the vehicle to determine if a recovery area has been identified. Once this identification has occurred, the UAV will enter a controlled descent, utilizing a stream of data from its vision system to align itself with the center of the recovery area. The UAV will descend to 1-2 feet above the recovery area, at which point the FCC will slowly land the vehicle. Once the vehicle has landed at the recovery area, the mission may proceed to Phase 5. A functional flow diagram describing Phase 4 of the mission is seen in the figure below.




**Phase 5: Sample Recovery**

The fifth and final phase of the mission is the recovery of the lunar ice sample. Upon landing at the recovery site at the end of Phase 4 of the mission, the ice mining and procurement system will be engaged. This system's rotating cylindrical scoops will begin to actuate, collecting pieces of lunar ice material. After the completion of this operation, the GCS will send a take-off signal to the UAV. Upon receiving this signal, the UAV will gently lift itself 10-20 feet above the ground, and fly 50 feet away from the recovery area. Finally, after executing this maneuver, the GCS will send a signal to the UAV, executing a final landing sequence. Upon landing, the mission will be complete.

## 4.2. System Level Conceptual Design Selection

In order to meet the requirements inherent to this mission, a sophisticated design solution must be developed. In order to accomplish this, a high-level design methodology was developed to help analyze and compare a myriad of conceptual designs. The differences in these designs center around different concepts for retaining and deploying the UAV payload. Additionally, two different concepts for the configuration of the airframe were considered, as well as their respective integration with the retention and deployment system.

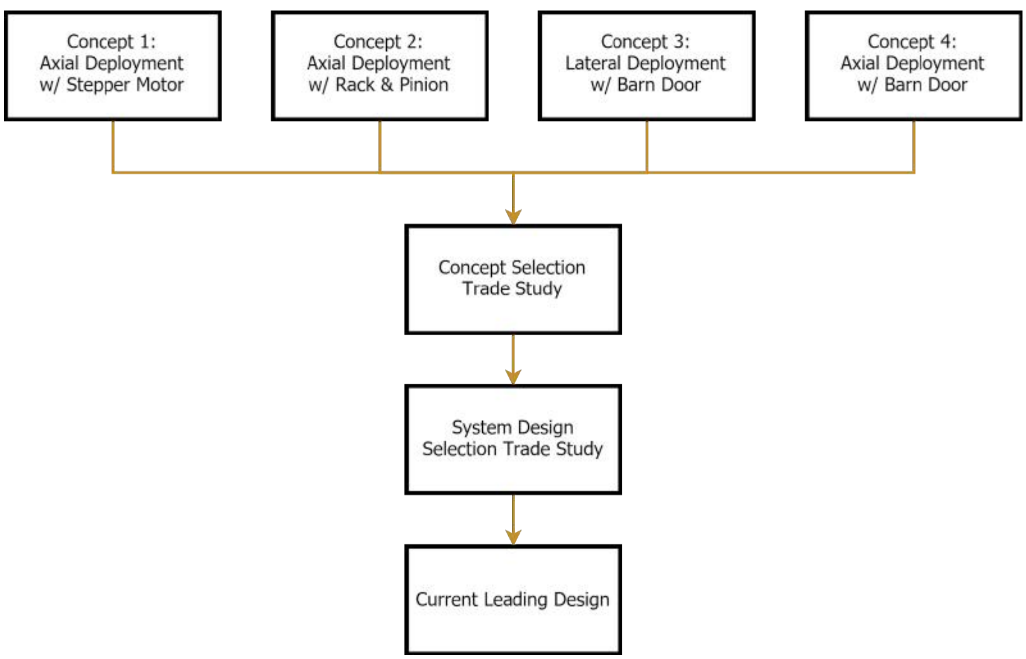
Retention and deployment concepts hinged on two different geometric methods of removing the UAV from the launch vehicle. The first of these methods that was discussed was a lateral deployment scheme, in which the UAV would exit through the side of the launch vehicle. A "barn door" style mechanism would replace a section of the airframe of the launch vehicle between the upper-airframe and the nose cone. This system would stay closed throughout the duration of the flight before actuating open at the start of the UAV's mission. The second retention and deployment concept employed an axial deployment scheme, in which the UAV would exit the launch vehicle through an opening created by an axial separation. This separation would be facilitated by a linear actuator in the payload bay.

The configuration of the airframe was another major design feature that had multiple high-level solutions to compare. The design of the airframe needs to solve two major problems in order for the payload to have a successful mission. First, the airframe must be able to fit securely inside the payload bay throughout the launch vehicle's flight. The difficulty of this problem stems from the geometry of the UAV's flight configuration. While flying, the UAV's four arms are at 90 degree angles from each other, a configuration that would not fit inside the 6-inch airframe of the launch vehicle. Multiple solutions that would allow the UAV's arms to actuate from a folded position into a flight configuration were considered. Additionally, the airframe design would need to be able to physically support all of the various mechanical and electrical components necessary for autonomous flight. Multiple airframe configurations were considered to solve this problem including a 3D-printed shelf-based design and a Nylon 6 plate-based design.

### 4.2.1. Design Methodology

The trade between the two retention and deployment concepts centered on the complexity of the solution and the amount of required modification to the launch vehicle's airframe. It was important to consider the impact of the payload's design on other parts of the overall design of the launch vehicle. Manufacturability was of particular concern. Superior operation and performance of a given design would only be a factor if the design could be executed in an accurate, safe, and cost-effective manner. An additional factor that was considered when comparing retention and deployment methods was the residual impact on the rest of the launch vehicle. The design of the payload did not take place in a vacuum, therefore payload designs that forced modifications to the design of the launch vehicle itself were not ideal.

The trade between airframe concepts was based primarily on the design's ability to reliably actuate between folded and flight configurations, as well as the design's ability to interface with the payload bay. It was essential to develop an airframe design that would inspire sufficient confidence that the UAV airframe would unfold correctly during the mission. Designs that relied on passive actuation systems were favored to mitigate the additional inherent failure modes of active systems. Analysis of the interface with retention and deployment mechanisms in the payload bay was also of principal concern. Airframe designs that could be more reliably retained throughout the launch vehicle's flight were favored.




### 4.2.2. Payload Conceptual Design Selection

After conducting detailed analyses of the aforementioned design concepts, a leading design was chosen that best fit the design criteria.

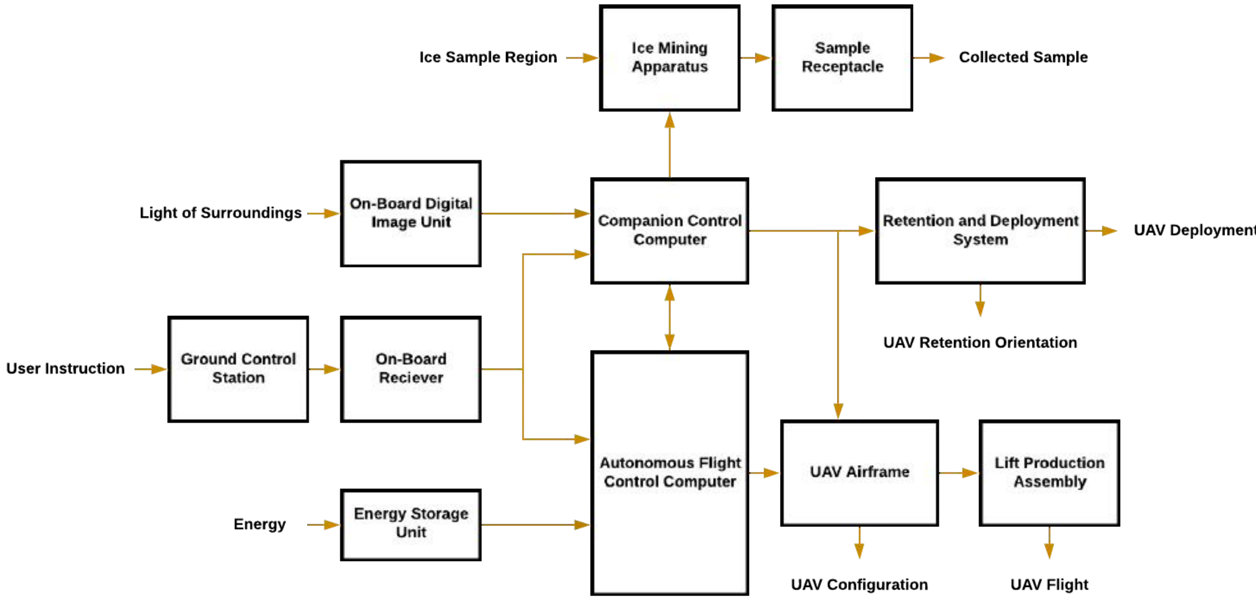
An axial deployment scheme, actuated by a through-type stepper motor was selected as the leading method for retention and deployment of the UAV. The alternative lateral deployment method was surpassed for two reasons. The primary reason concerned the difficulty of manufacturing a lateral-deployment design. Cutting a door into the side of the fiberglass airframe of the launch vehicle added unnecessary risk to the project. The axial deployment scheme can be implemented without drastically altering the existing geometry of the launch vehicle. Additionally, the axial deployment design would not alter the overall configuration of the launch vehicle, whereas the lateral deployment scheme necessitated altering the launch vehicle's overall weight distribution. More details concerning the axial deployment leading design are given below.

The leading airframe design is molded by the criteria described above. To solve the problem of actuating the UAV's arms, a passive, spring-based design was chosen. This design takes advantage of the active retention and deployment system to hold the wings of the UAV against the interior wall of the payload bay. As the payload bay separates during the deployment phase of the mission, the energy stored in a spring on the UAV forces the wings into their flight configuration. Employing a passive system to solve this task mitigates the failure risk inherent to an active design. A nylon 6 plate-based design was selected as the leading design for the configuration of the airframe. This design struck a balance between high strength, low weight, and useful geometry. The design employs stand-offs to separate multiple nylon 6 plates for holding the various electronic components necessary for autonomous flight. Additional details of this design are outlined below.

## 4.3. Selection, Design, and Rationale of the UAS

### 4.3.1. UAS Subsystem Overview

The UAS is responsible for autonomous flight, navigation to an ice mining recovery area, and procurement of the lunar ice sample. The system is broken down into two primary subsystems: the UAV and GCS. The UAV employs a quad-rotor design with an innovative folding method, allowing the vehicle to fit inside the airframe of the launch vehicle and interface with the R&D system. The UAV has a sophisticated flight control system and mission management system for controlling autonomous flight, including a computer vision system for autonomous recognition of recovery areas. An ice mining and procurement system is integrated into the lower section of the UAV, allowing for ample recovery of simulated lunar ice material. The diagram below shows how these subsystems are integrated together to accomplish the requirements of the mission.




The GCS provides the bridge between the UAV and the operators overseeing the mission on the ground. This system allows for full mission control capability, allowing for the initiation of various phases of the payload mission, emergency shutdown, and other control functionality discussed below. The GCS also facilitates real-time telemetry streaming from the UAV, allowing for intelligent decision making throughout the course of the mission. These subsystems, as well as the trades between design alternatives, are discussed at length below.

### 4.3.2. Flight Control System (FCS)

The flight control system provides the UAV with attitude and altitude control and is comprised of a flight control computer and an integrated GPS and compass unit. The flight control computer (FCC) will require an integrated sensor set that provides data necessary for position estimation and also contains the control laws necessary for UAV flight. The GPS will augment the inertial data provided by the FCC and also provide GPS guidance capability for autonomous flight.

#### Flight Control Computer (FCC)

In order to provide the autonomous capabilities necessary to complete the mission, the FCC requires sensors that provide barometric pressure, 6-axis acceleration, magnetometer data, and GPS data. Autonomous flight capable boards that are readily available off-the-shelf meet these requirements and come with open-source software that can be modified to fit the needs of the user. Of the commercially available and open-source FCCs, the Pixhawk 4, the Pixhawk 4 mini, and the CUAV Nano V5 were selected for comparison.

All three of these boards are autonomous flight capable and can be integrated with a similar level of complexity to the other UAV electronics. Of these three boards, both Pixhawk boards have inertial sensors mounted on internal vibration damping pads while the CUAV V5 does not. This means that the CUAV V5 will require externally vibration damping that will take up weight and space. In terms of electrical connections required by the UAV, all of the flight controllers have enough connections and processing power for sufficient data handling between the telemetry unit, the GPS/compass, the companion computer, and the RC radio receiver. As these three flight boards meet all the requirements for the FCC, the selection criteria were placed primarily on power consumption, size, weight, and cost. The decision matrix and selected FCC can be seen in the table below. The maximum rating an item may receive in any category is a 1.0 and scores are given on a quantitative basis for all of the criteria.

| Criteria | Weight | Pixhawk 4 | | Pixhawk 4 Mini | | CUAV V5 Nano | |
|---|---|---|---|---|---|---|---|
| | | Rating | Score | Rating | Score | Rating | Score |
| Power | 2 | .5 | 1 | 0.7 | 0.9 | 0.6 | 2.4 |
| Weight | 3 | 0.8 | 2.4 | 0.9 | 2.7 | 0.6 | 1.8 |
| Size | 3 | 0.8 | 2.4 | 0.4 | 0.8 | 0.5 | 1.0 |
| Cost | 2 | 0.4 | 0.8 | 0.7 | 1.4 | 0.4 | 0.8 |
| Total Score | 10 | | 6.6 | | 5.8 | | 6 |

The selected FCC for the leading design of the UAV is the Pixhawk 4. Although the Pixhawk 4 uses more power and is slightly more expensive than the Pixhawk 4 mini, the Pixhawk 4 excels in terms of size and weight which are the two most important considerations given by the stringent weight and envelope requirement of the UAV.

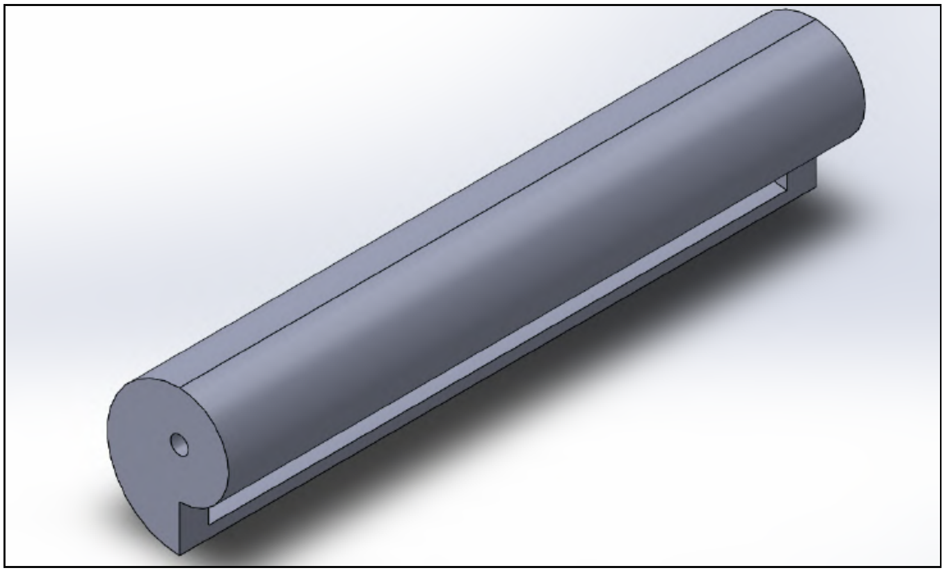
**GPS/Compass**

The GPS receiver and compass electronics used for mini UAVs are typically integrated and are used by the FCC to collect positioning data for use in mission guidance and position estimation. The combined GPS/compass chosen for use in the FCS is the Pixhawk 4 GPS module. It not only includes the minimal functionality requirement of a GPS and compass, but also includes a safety switch and indicator LEDs.

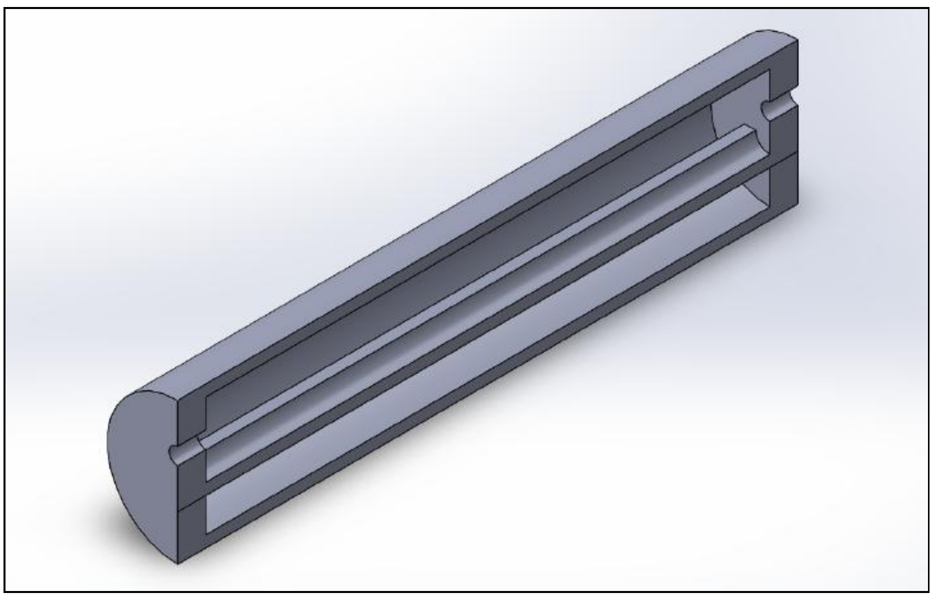
### 4.3.3. Ice Mining and Procurement System

The ice mining and procurement system (IMPS) will minimally collect the required 10mL ice sample once the UAV has identified and landed at the recovery area. Once the ice sample has been collected, it must be stored safely for UAV reflight and subsequent ice recovery. The design and method of ice collection was primarily based off of the size of the large granules and the system's placement on the UAV. Two designs were compared that both employed a rotating scoop method of collection but approached the space constraint on the UAV differently. The first involves the use of a pair of slender rotating scoops that counter-rotate between each of the UAV's legs while the second would employ four short rotating scoops of significantly reduced aspect ratio placed on each leg of the UAV.

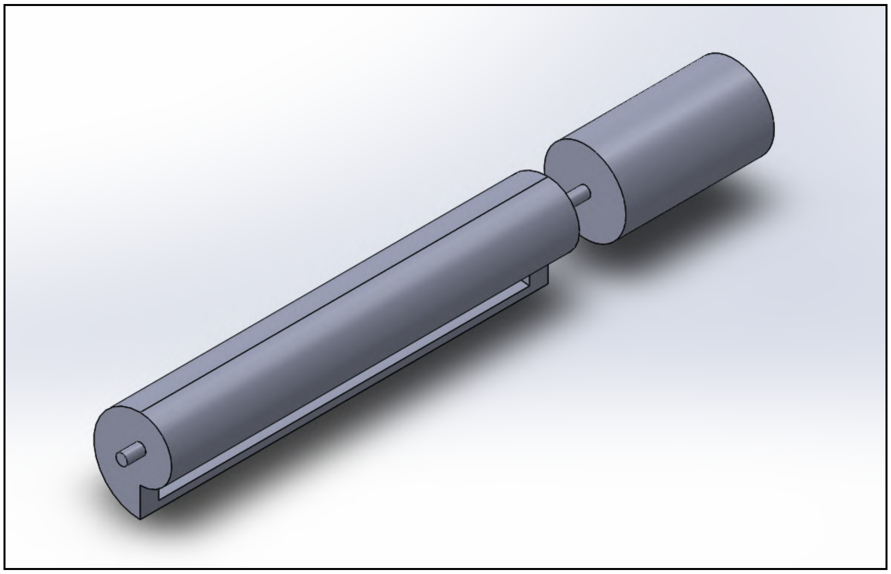
The first design employed one large cylindrical scoop that would rotate around an axis and collect the ice pieces as it spins. Below is an image depicting this design:



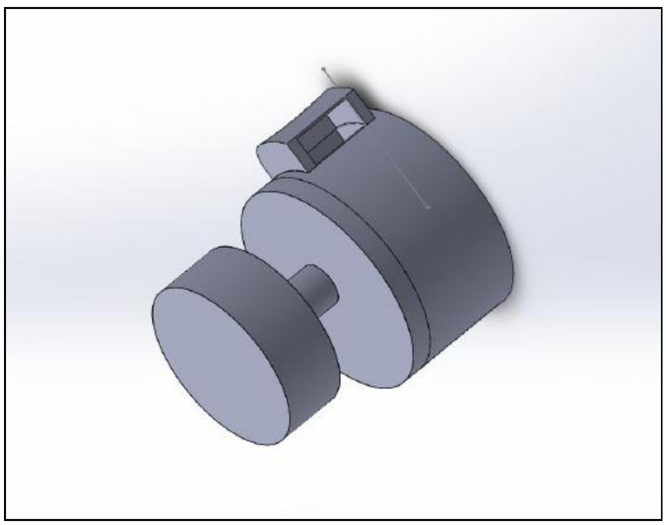
In order to make sure that the ice particles would not fall out after they were collected, the team created a container inside of the scoop that will contain the ice pieces. They will be contained by the small lip that is inside of the inner cylinder. Here is a sectioned view of the scoop:



To prevent the ice from falling out of the scoop as it is rotating, there will be two rods attached on either side of the scoop. One side of this will be attached to the motor so that the scoop will spin and the other side will be attached to a rod that will be able to rotate in place so that it can collect the ice. Below is an assembly that depicts the integration between the scoop and the motor.



The second design has a much smaller scoop mechanism that would only be capable of fitting a few grains of ice along its cross section. This design would require four different motors each with their own motor and attached to each of the UAV's legs. A model of the design is seen in the image below.



In order to quantify the differences between these two designs, a decision matrix was created. The comparison centered on a set of four design criteria: total volume, manufacturing ease, opening area, and capacity. Weights were given to each of these criteria. Total volume refers to the volume the design takes up on the airframe, whereas capacity refers to the amount of lunar ice material that the design can hold.

| | | Single Scoop | | Multiple Scoops | |
|---|---|---|---|---|---|
| **Criteria** | **Weight** | Rating | Score | Rating | Score |
| Total Volume | 2 | 0.9 | 1.8 | 0.8 | 1.6 |
| Manufacturing Ease | 3 | 0.8 | 2.4 | 0.6 | 1.8 |

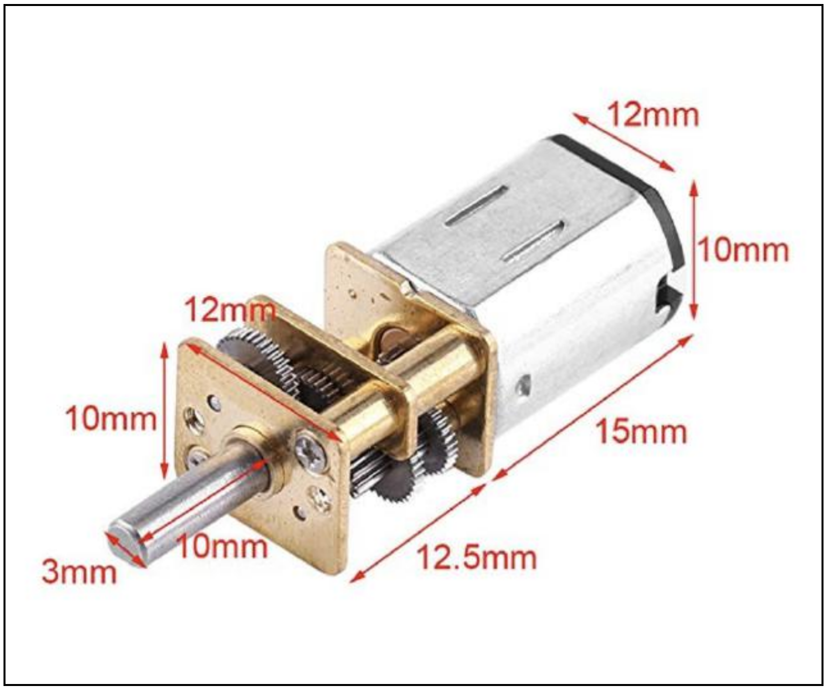
| | | | | | |
|---|---|---|---|---|---|
| Opening Area | 1 | 0.9 | 0.9 | 0.6 | 0.6 |
| Capacity | 4 | 0.8 | 3.2 | 0.7 | 2.8 |
| Total Score | 10 | | 8.3 | | 6.8 |

As seen in the table above, the current leading design is the single scoop. The first design is a better option because it will be able to collect the ice particles at a more efficient rate as the scoop is larger in size. There is more potential for the particles to fall out as the scoop is spinning with the larger scoop, however the larger scoop design allows for more sample collection with every rotation. The relatively small size seen in the second design was found to be a limiting factor, leading to concerns about its manufacturability.

In order to decide which motor is best for the ice procurement system a decision matrix was employed. The torque, weight, length, diameter, and cost were considered.

| Criteria | Weight | DC 6V | | FIT0495-A | | FIT0495-B | | FIT0495-E | |
|---|---|---|---|---|---|---|---|---|---|
| | | Rating | Score | Rating | Score | Rating | Score | Rating | Score |
| Torque (Ncm) | 5 | 0.5 | 2.5 | 0.8 | 4 | 0.7 | 3.5 | 0.3 | 1.5 |
| Weight (g) | 5 | 0.9 | 4.5 | 0.3 | 1.5 | 0.3 | 1.5 | 0.4 | 2 |
| Length (in) | 3 | 0.8 | 2.4 | 0.5 | 1.5 | 0.5 | 1.5 | 0.5 | 1.5 |
| Diameter (in) | 5 | 0.9 | 4.5 | 0.7 | 3.5 | 0.7 | 3.5 | 0.7 | 3.5 |
| Cost ($) | 2 | 0.8 | 1.6 | 0.9 | 1.8 | 0.9 | 1.8 | 0.9 | 1.8 |
| Total Score | 20 | | 15.5 | | 12.3 | | 11.8 | | 10.3 |

As seen above, the "DC 6V" motor was selected as the leading choice. It is significantly lighter than the other motors as it only weighs 10g and the others weighed between 72-74g. It is important to have a light motor, especially since there will be two motors, one for each side of the ice mining system. It is also much smaller than the other motors, having a diameter of 0.472 in and a length of only 1.48 in. The other motors had a diameter of roughly an inch and a length of just over two inches. All of the motors were around the same price, the three that were not chosen were $10.20 and the leading motor choice is $10.99. The only drawback of this motor is that it does not have as high of torque as some of the other motors. Below is a picture of the motor with the size dimensions alongside it:




### 4.3.4. Mission Management System

The mission management system (MMS) will handle the processing of incoming commands from the GCS and issue all setpoint altitude and setpoint position data to the FCS that will control flight of the UAV. The mission management system is primarily comprised of three components: the mission control unit (MCU), the AGL altimeter, and the digital imaging unit.

**Mission Control Unit (MCU)**

The Mission Control Unit is the brain of the entire Mission Management System. The MCU needs to be able to communicate with two different systems (FCS and IMPS) as well as gathering and parsing information from the Altimeter Sensor and the Digital Imaging Unit (DIU). While the MCU is not directly responsible for UAV flight it will be responsible for sending the direction data needed to help navigate the payload toward the ice procurement area. Once at the ice procurement area the MCU will also be responsible for sending the signals to start the ice mining and to finish ice mining.

Because of the amount of tasks that the MCU needs to accomplish, a microcomputer was chosen for it's design. While arduino was considered for its ease of use it is not the best computing unit for doing multiple tasks at once and not good for process intensive tasks. The MCU will be responsible for parsing the images received from the DIU. Knowing this, a more powerful microcomputer running a Linux like operating system chosen.

**AGL Altimeter Sensor**

The AGL altimeter will provide above ground level (AGL) data to the MCU that will be used for recovery area identification and validation. This information will be used directly for the inertial estimation of the UAV position and will also be used when descending towards and tracking the recovery system meaning that high accuracy is a requirement. By itself, the FCC estimates AGL altitude using a barometric sensor to measure relative altitude from its takeoff point along with digital terrain elevation data (DTED). In order to better control trajectory during descent and to better identify and discriminate the recovery area, it was determined a distance sensor would be required to augment the barometric sensor in use by the FCC.

Of the commercially available distance sensors, the LiDAR Lite v3, LiDAR Lite v4, and the TFmini had an acceptable operational range, power consumption, weight, and price that allowed for their further consideration. The distance sensor was selected using a decision matrix with the criteria of maximum operational range, power draw, weight, and cost with the operational range having the highest scoring weight since a larger operational range would mean a higher flight-ceiling when searching for the recovery area.

| Criteria | Weight | LiDAR Lite v3 | | LiDAR Lite v4 | | TFmini | |
|---|---|---|---|---|---|---|---|
| | | Rating | Score | Rating | Score | Rating | Score |
| Range | 4 | 0.9 | 3.6 | 0.3 | 1.2 | 0.2 | 0.8 |
| Power | 2 | 0.5 | 1.0 | 0.7 | 1.4 | 0.8 | 1.6 |
| Weight | 2 | 0.5 | 1.0 | 0.6 | 1.2 | 0.8 | 1.6 |
| Cost | 2 | 0.4 | 0.8 | 0.6 | 1.2 | 0.7 | 1.4 |
| Total Score | 10 | | 6.4 | | 5.0 | | 5.4 |

The selected altimeter sensor being used is the LiDAR lite v3. The LiDAR lite v3 has the highest operational range of 130ft compared to the LiDAR Lite v4 and the TFmini with a maximum range of 30ft and 16ft respectively. Although the LiDAR Lite v3 weights a bit more than the other two options and consumes a bit more power, the functionalities enabled by its extended range made it a leading choice for the AGL altimeter sensor.

### Digital Imaging Unit (DIU)

The Digital Imaging Unit is the base of what will be used for locating the lunar ice. The DIU is a digital camera that will be connected to the MCU and will supply image data for subsequent processing. The DIU will be mounted to the bottom of the UAV and periodically take pictures of the ground which will be sent to the MCU which will analyze the picture to guide the UAV to the lunar ice.

The selection of the DIU involved consideration of whether the DIU would be processing the image data, and if it was, how much processing would it be doing. Because of weight, size, and power restrictions, the programs that would be run to analyze the pictures would be run on the MCU. That means the DIU is actually consists of two parts. The physical camera and non physical program of the image analyzation.

In choosing the camera there were two different types that would, going forward, affect the upfront amount of program creation that would have to be completed. Integrated computer vision (CV) boards are camera boards that have built in programs that interpret images and videos. The three most popular examples of these are OpenMV, Pixy2, and Jevois. The reasons these were considered as potential DIU units were because they have built in software that can recognize characteristics such as different shapes and colors. That ability would be useful for the detection of the tarp holding the lunar ice either via rectangle detection or color change. The second choice for camera use were “PI cameras”, called that because of the similarity towards the Raspberry Pi Camera Module series. These cameras, when used with raspberry pi libraries, have the ability to take pictures and videos at specified times and intervals but can't do anything more complicated than adding filters. In order to do the necessary image analysis, the team would need to develop their own image processing software.

In comparing the CV Boards and the PI cameras, the CV boards looked more desirable because of their built in functions. However, the costs of the CV boards and the amount of power they require made it inconvenient for use with the payload as many components need to be powered for an indiscriminate amount of time. Therefore the PI cameras were chosen to be the camera used for the DIU. A weighted-decision matrix showing this trade-off is seen below.

| Criteria | Weight | CV Boards | | PI Cameras | |
|---|---|---|---|---|---|
| | | Rating | Score | Rating | Score |
| Power Efficiency | 3 | 0.4 | 1.2 | 0.8 | 2.4 |
| Open Source Documentation | 3 | 0.5 | 1.5 | 0.6 | 1.8 |
| Ease of Use | 2 | 0.9 | 1.8 | 0.4 | 0.8 |
| Cost | 2 | 0.4 | 0.8 | 0.9 | 1.8 |
| Total Score | 10 | | 5.3 | | 6.8 |

**Recovery Area Identification**

Identification of the recovery area will involve the use of range sensors, approximate GPS data, and computer vision methods. Before launch, approximate GPS data of recovery areas will be gathered and subsequently programmed into the mission plan. During the recovery area searching phase, the UAV will autonomously travel to the closest programmed GPS point. Once the UAV is near the recovery area, imaging data will be processed by the MCU to detect and discriminate the tarp and ice deposit using color isolating and contour detection methods. The processed image data will be used to feed the FCS position setpoint data until the UAV is hovering directly over the ice deposit. The UAV will then slowly descend until it lands while keeping the ice deposit directly beneath it.

### 4.3.5. Ground Control Station

The ground control station (GCS) provides the physical interface between the pilot in command and the UAV. It includes any and all communication interfaces between an operator, the UAV, and the payload retention and deployment system that will be necessary to complete the mission. Its functionalities include monitoring TM data, viewing image data, autonomous mission planning, monitoring mission status, flight mode switching, and an emergency stopping. In summary, the GCS will combine functionalities commonly seen in laptop GCS setups with an interactive mission control panel that allows for quick and informative decision making. The GCS will run parallel to an RC radio transmitter that will act as a redundancy and a fall back in case manual control of the aircraft is required.

The GCS is primarily comprised of four components: the display head assembly (DHA), the mission control panel (MPC), the mission control computer (MCC), and the wireless datalinks. The DHA is primarily a single LCD monitor that will display real-time flight data, image data, and mission data relevant to safe and informed UAV operation. The MCP is a set of switches, buttons, LEDs, and a keyboard that provides complete control over the UAV during flight testing and general operation. The MCC is the computing unit that will handle all data passed from and to the GCS as well as displaying all relevant operational data to the GCS operator. Finally, the wireless data links provide two-way communication from the GCS to the UAV, and the GCS to the R&D system. The figure below is a representation of how all the components of the GCS interface with each other. The mission control computer lies at the center of the GCS which interprets and store all data coming in from the MCP and the wireless data links then display requested information to the DHA.

The physical design of the GCS is a portable computer installed in a protective casing that opens up to a monitor and a control panel. The GCS functions as a laptop computer augmented with UAV control and monitoring electronics. A CAD design of the preliminary GCS is presented in the figure below.

### Mission Control Computer (MCC)

The mission control computer handles the storage and communication of all data inside the GCS, from the GCS to the UAV, and from the GCS to the R&D system. It will communicate to and from these components through a variety of methods and protocols including UART, serial and I2C. In order to perform the processing and interfacing requirements necessary, the MCC must include at least one USB port, a GPIO interface, a storage unit or an interface with a storage unit, low power requirements, and the capability to run an operating system (OS). Given these requirements, the Raspberry Pi 4, Nvidia Jetson Nano, and the ODROID-C2 were considered as a viable choice for the MCC. All of these microcomputers have considerable computational power necessary for the operation of the GCS and meet all of the requirements previously stated.

The Raspberry Pi 4 (RPi4) is a recently released microcomputer capable of running a Linux OS and therefore all the software necessary for UAV control. Of all the options, the RPi4 has the most documentation and the most software libraries that make it easy to interface and communicate with numerous switches and displays. The RPi4 has an idle power consumption of just under 3W and has 40 GPIO pins that include SPI, UART, and I2C communication.

The Nvidia Jetson Nano is a small but powerful computing platform with a powerful GPU. Similarly to the RPi4, the Jetson Nano is capable of running a Linux OS. The Jetson Nano, like the RPi4 also contains similar software libraries for I/O applications but does not have the extensive documentation and community that the RPi4 does. The Jetson Nano has an idle power consumption of 4.5W and also has 40 GPIO pins that also enable SPI, UART, and I2C communication.

The ODROID-C2 is a single-board computer of similar size and configuration to the RPi4. It has the same number of GPIO pins with the same communication protocols and the same number USB inputs. Computationally, the ODROID-C2 has the advantage with a more powerful CPU with a higher clocking speed. This board is also capable of running a Linux OS with an idle power consumption of 2W.

In order to select the MCC, a decision matrix was prepared with criteria including cost, power, computational power, and ease of implementation. Of these criteria, the most scoring weight was placed on power and computational power. The decision matrix and selected MCC can be seen in the table below. The maximum rating an item may receive in any category is a 1.0 and scores are given on a subjective level for expected ease of use and a quantitative basis for power, computing speed, and cost.

| Criteria | Weight | Raspberry Pi 4 | | Nvidia Jetson Nano | | ODROID-C2 | |
|---|---|---|---|---|---|---|---|
| | | Rating | Score | Rating | Score | Rating | Score |
| Power | 3 | 0.7 | 2.1 | 0.3 | 0.9 | 0.8 | 2.4 |
| Computing Speed | 3 | 0.5 | 1.5 | 0.9 | 2.7 | 0.6 | 1.8 |
| Ease of Use | 2 | 0.9 | 1.8 | 0.4 | 0.8 | 0.5 | 1 |
| Cost | 2 | 0.8 | 1.6 | 0.5 | 1 | 0.6 | 1.2 |
| Total Score | 10 | | 7 | | 5.4 | | 6.4 |

The selected MCC for the GCS is the RPi4. Although the RPi4 does not consume the least power nor does it have the fastest computing speed, it excels in terms of ease of implementation and its low cost. The libraries, community, and surplus of available documentation make the RPi4 a strong choice given the stringent budget and schedule requirements and will allow for the quick integration and deployment of the GCS.

### Display Head Assembly (DHA)

The DHA is a set of two displays that will provide real-time flight telemetry data, flight imaging data, and mission status to the operator to allow for safe operation of the UAV and an ability for the operator to make quick and informed decisions. The primary display of the DHA is a 15.6” LCD monitor that will connect directly to the MCC using an HDMI cable, while the secondary display is a 3.2” LCD monitor that will connect to the MCC using a serial interface. The primary monitor will display up-to-date time-space-position information (TSPI) data in the form of a cursor on a satellite image, flight attitude data, AGL and MSL altitude data, onboard camera imaging data, and mission status. The secondary monitor will provide battery data of both the UAV and GCS along with their respective remaining time of operation. A set of speakers will also provide notable changes to the operation of the UAV which include flight mode switches, violations of pre-programmed flight paths, battery warning, and any other faults that threaten the safe operation of the UAV. Presented in the figure below is the preliminary design of the DHA with a display showing GPS data, image data, and TM data on the primary display with the secondary display empty just below it.

An alternative setup was considered using a set of three displays with two smaller displays replacing the single primary display. This alternative was not selected as it would introduce increased complexity between the MCU and DHA, increase power consumption, and reduce display area, all at a similar cost.

### Mission Control Panel (MCP)

The MCP is an integrated control interface that allows for complete control over the operation of the UAV during flight testing, mission operation, and other general operation. The MCP allows for quick selection of the UAV flight mode, emergency stopping through use of a kill switch, arming and disarming of the UAV, and finally the direct control of mission procedures. This functionality is primarily allowed through the use of push-button switches and toggle switches. Feedback is given to the operator through the use of LEDs and a 20x4 character LCD display that presents information on UAV mission status.

Control of the mission is divided into 6 discrete actions that are subsequent to recovery and must follow go/no-go requirements before the mission may proceed. These six controllable actions are as follows: deployment of the UAV from the payload bay, orientation correction after a successful deployment, arming of the UAV after reaching a flight ready orientation and configuration, recovery area search and approach, ice procurement, and finally sample recovery. Both the UAV deployment and UAV orientation buttons do not have any programmed entry/exit requirements and the use of these two actions is left to the judgement of the operator. The latter four steps have pre-programmed entry/exit criteria and must be followed in sequence. The pre programmed criteria include items relevant to the safety of operation of the UAV and other required information and data. For example, the UAV may not proceed to arm unless a GPS lock is obtained. Information related to the operation and control of the mission will be displayed on the 20x4 LCD monitor. If an operator attempts to proceed with the mission without meeting all of the entry/exit criteria, a message will appear on the 20x4 LCD monitor detailing why. Presented in the figure below is the preliminary configuration of the primary switches and the vehicle status display that will be used during the mission.


In addition to the switches and buttons being used to control the mission, an emergency push button will be installed on the bottom-right of the MCP interface. In the event of unexpected flight behavior or a flight trajectory that may lead to a mishap, engaging the kill switch will immediately disarm the UAV and terminate all power to all auxiliary actuators used for ice procurement. Upon engaging the kill switch, the MCC will confirm the flight termination of the UAV and will enable a loud buzzer to let the operator know that the flight terminated successfully. This buzzer will also be active and beep repetitively when the battery of the GCS or UAV reaches a predefined threshold yet to be determined.

Nine different flight modes are given direct control through the MCP. The nine flight modes are the following: mission, offboard, manual, stabilized, position, takeoff, land, return to base, and follow. The primary flight modes used in testing and mission operation will be mission, return to base, and land. The other six flight modes will be used primarily in integration testing, flight testing, ground testing, and computer vision algorithm testing. Of these nine flight modes, only one flight mode may be active at once and the entry/exit of certain flight modes must meet criteria. For example, one may not enter a mission flight mode if they do not have all the equipment necessary for that mission. The table below provides a basic description of the nine selectable flight modes.

| Flight Mode | Description |
|---|---|

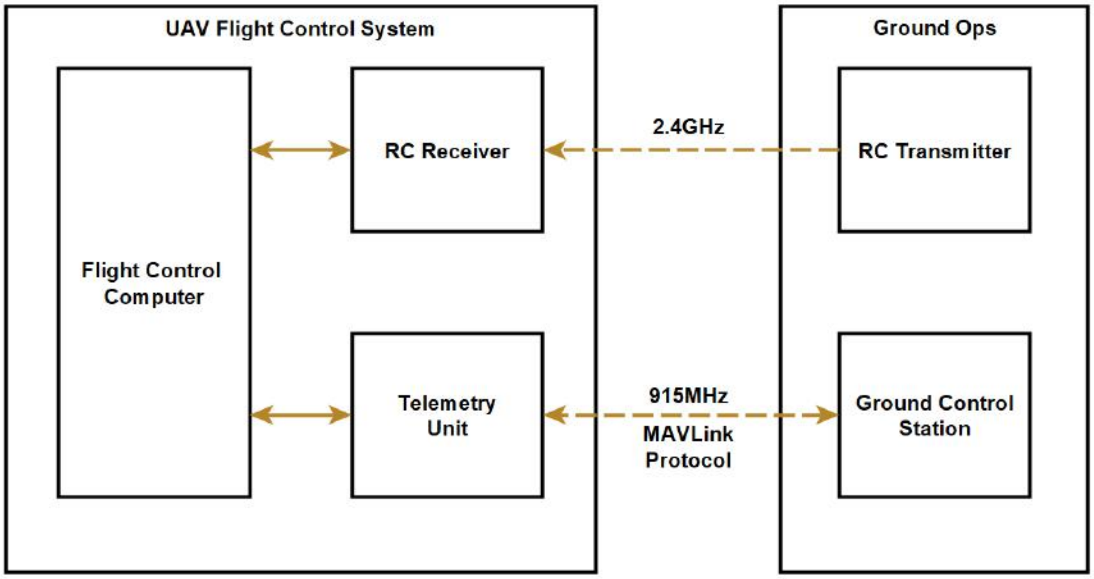
| | |
|---|---|
| Mission | UAV control is given to the preprogrammed mission starting from UAV deployment to ice sample recovery |
| Offboard | External control using setpoint north-east-down and altitude data from an external computer. |
| Altitude | UAV movement limited to a plane of constant altitude |
| Position | Hold position |
| Manual | External control using a joystick or RC Radio |
| Takeoff | UAV takeoff to a programmed altitude |
| Land | UAV landing |
| Return to Base | UAV returns to a programmed home position followed by a landing |
| Follow | UAV tracks and follows GPS of GCS |

#### RC Radio Transmitter

In addition to the GCS, an RC radio transmitter will be used for the manual and altitude stabilized control of the UAV in testing and general operation. The RC transmitter will be operated in parallel with the GCS but will not be required for mission operation; it will be used initially for flight qualities testing and as a backup when quick manual control of the UAV is required. Since the function of the RC transmitter only requires the manipulation of flight mode and 6-axis control, the most important consideration used in its selection is cost and availability. The selected RC transmitter is the Taranis Q X7 as it is relatively cheap but popular RC radio capable of controlling the UAV.

### 4.3.6. Communication and Data Links

Communication to the UAV is allowed through the GCS or an RC Transmitter. The UAV will have both an RC receiver and a telemetry unit that will be used to receive commands and send data regarding status. The RC transmitter will send data at a frequency of 2.4GHz, while the data links between the GCS and the UAV will communicate at a frequency of 915MHz. The diagram below depicts the data-flow between all data-links of the UAS.




The Telemetry unit that will be installed on both the GCS and the UAV will be the 915MHz Holybro Transceiver Telemetry Radio with an adjustable transmitter power of 100mW. Other options for telemetry radio operated on the same frequency band, but offered a greater output power and therefore a greater range. Based on the maximum expected operational ranges, the 100mW power output should be sufficient, however, testing will be conducted to verify this range. Communication between the telemetry radios will use the open-source Micro Air Vehicle Link (MAVLink) Protocol. The MAVLink protocol enables the sending of status data, command and control data, and image data.

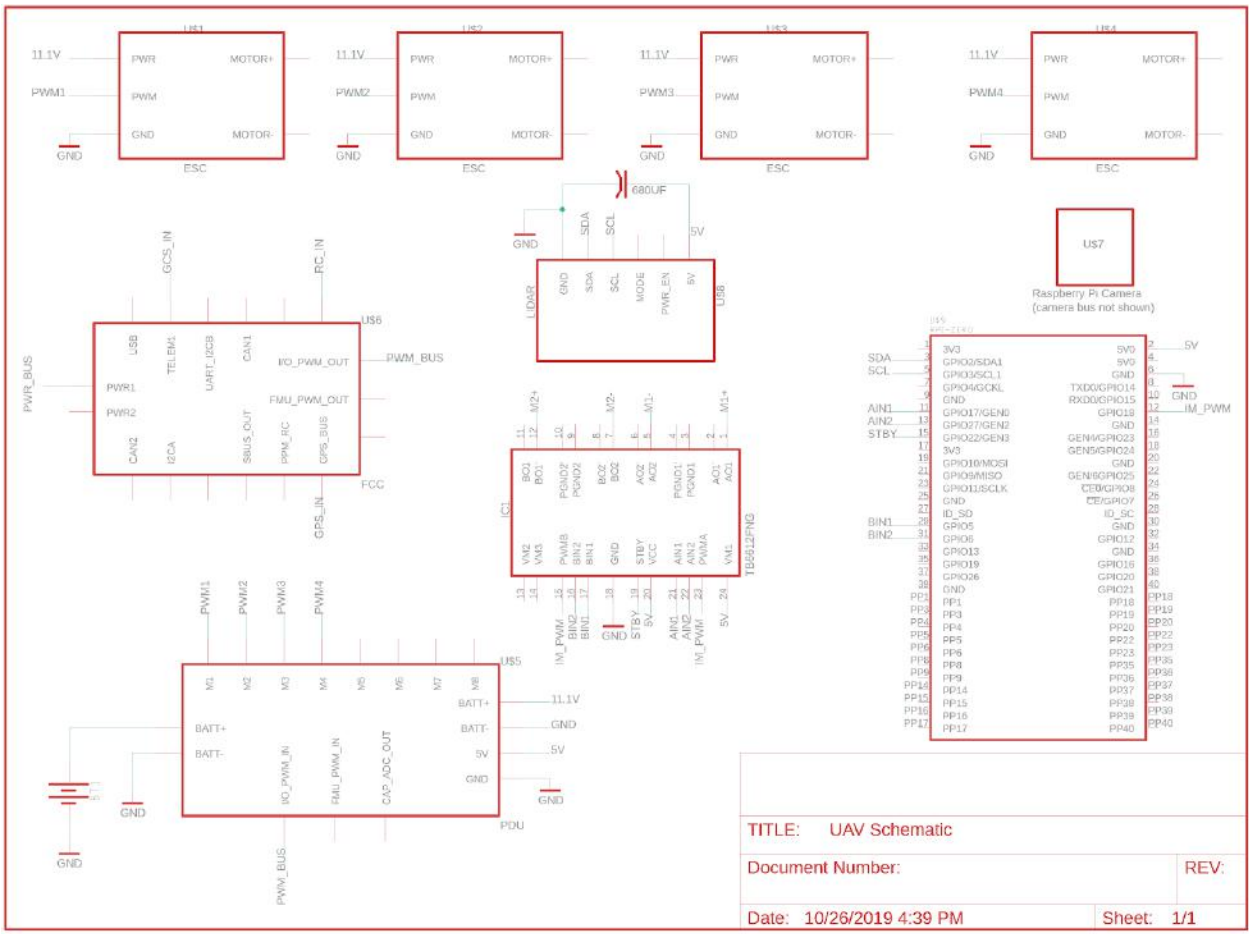
The RC transmitter will provide one-way communication to the RC Receiver on the UAV. Data sent from the RC transmitter will control flight modes, thrust, roll rates, pitch rates, and yaw rates. The selected RC receiver is the FrSky XSR receiver chosen primarily due to its low weight of 4.3g and compatibility with the chosen RC Transmitter.

### 4.3.7. UAV Batteries and Power Distribution

A sophisticated power system, including a battery and power distribution system, must be implemented on the UAV. This system shall deliver proper voltages and currents to all electrical components in the system, including flight control, image processing, and ice mining components. This system provides the sole source of energy for the UAV. For this reason, adequate energy capacity must be combined with intelligent power consumption to ensure the UAV is powered throughout the entirety of the mission.

At the heart of the power system on-board the UAV is an 11.1 V lithium polymer (LiPo) battery. Lithium polymer battery technology was selected for this application for two primary reasons. First, LiPo batteries are ubiquitous in hobby UAV and RC applications due to their high energy density. LiPo batteries provide higher amounts of energy for less weight than other battery technologies such as nickel cadmium or nickel metal hydride. This is an essential feature for small, airborne applications such as a UAV. The second reason for choosing a LiPo battery to power the UAV is the technology's higher current discharge rate. In general, LiPo batteries are better for higher-current applications than competing technologies. Quadcopter UAV configurations are an example of such a high-current application. Each of the UAV's four motors could draw on the order of 2-5A of current. A LiPo battery is well suited to meet this power requirement.

The energy supplied by the LiPo battery must be safely distributed to the various electrical components on-board the vehicle. These components, such as the flight computer, the ice mining system, and the electronic speed controllers, operate with different power requirements. To fulfill this need, a power distribution system, based on Pixhawk 4 Power Management Board, is employed. This device was chosen because it is specifically manufactured for the purpose of distributing power safely to the Pixhawk 4 flight computer and associated UAV peripherals. Presented below is a block diagram displaying the power distribution on-board the UAV.




An alternative solution, based on a custom-designed printed circuit board, was considered as well. Ultimately, however, the reliability of using a proven, off-the-shelf solution like the Pixhawk 4 Power Management Board was the determining factor. This would allow for greater risk mitigation and quicker development time than seen in an entirely custom solution.

### 4.3.8. Propulsion System

The propulsion system is a set of electronic speed controllers (ESC), brushless DC motors, and propellers that work together to produce thrust that drive the UAV. Selection for each of these components was done separately but sequentially. First, an optimal propeller was chosen that fit the spacing constraints of the vehicle while maximizing flight time, then a motor was selected based on the power and torque requirements of the propeller, and finally an ESC was selected that matched the power requirements of the motor.

Given the spacing requirements necessitated by the UAV while stored in the launch vehicle and the space required when the UAV is deployed sitting on the sled, it was determined that the propellers were needed to be foldable for compact storage and must be capable of being unfolded when the motors are spinning at an idle throttle. Looking towards the design of the propeller, a propeller that contacts more air (i.e. a propeller that is larger) and a propeller with a lower pitch angle gives the most efficiency and therefore the most flight-time but come at a cost of maneuverability.  Since mission performance does not depend on the maneuverability of the vehicle, the largest propeller with the lowest pitch that would fit the spacing requirements was chosen. The chosen propeller is the Advanced Precision Composites 7x4F.

Performance data for the selected propeller is available from the manufacturer and can be used to calculate power and torque data that can be used to estimate flight-time and select a compatible motor. Calculations were made at varying thrust-to-weight ratios and at varying vehicle velocities to determine worst case scenario flight-times and an optimal travel speed. Summarized below is a table of vehicle flight times assuming an efficiency of 75% as power travels from the ESC to the motor and finally to the propeller.

| Thrust-to-Weight Ratio | 0 mph | 5 mph | 10mph |
|---|---|---|---|
| 1.0 | 17.2 | 16.5 | 15.9 |
| 1.5 | 10.4 | 10.0 | 9.6 |
| 2.0 | 6.9 | 6.6 | 6.4 |

Assuming an average thrust to weight-ratio of 1.5 and an average speed of 5 mph throughout the mission, the UAV has an estimated flight time of 10 minutes before the battery empties or about 8 minutes before the UAV must immediately land to ensure safety. Given that the estimated flight-time of the mission is 6.5 minutes, the UAV will have an additional 1.5 minutes for contingency searching or an additional operational battery margin of 550 mAh.

Selection of the motor primarily involved minimizing weight and size and matching power requirements. In order to minimize space, the motors were required to mount underneath its structural attachment so that the propeller shaft would run the structure and the propeller would lie just above it. Based on the maximum expected thrust-to-weight ratio of 2.0 and a maximum speed of 10mph, the motor was required to be able to output 70W of power. Based on this criterion, the lightest motor found that fit mounting, sizing, and space requirements was the Turnigy Aerodrive SK3 – 2822. The ESCs that were subsequently selected were based on the matching the motor current requirement while minimizing weight. The ESC selected was the Turnigy Multistar ARM 21A since it more than doubles the 10A motor current requirement while being relatively lightweight and space efficient.

### 4.3.9. Airframe

#### 4.3.9.1. Structural Design

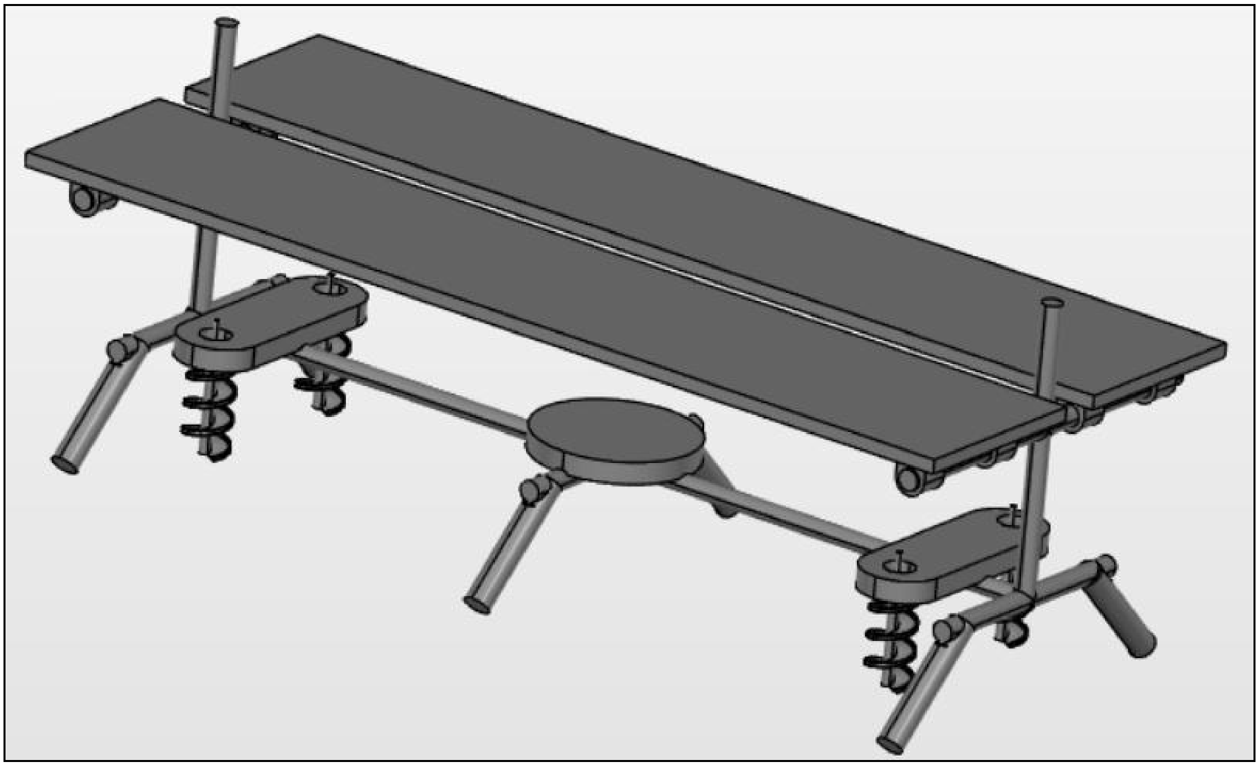
All hardware and electronic components need some form of structural support in order for the UAV to be functional. The airframe needs to support the weight of all the sub-components and along with that, the design needs to consider center of mass as one of the important factors. More importantly, the airframe also needs to be contained within the constraints such as the inner diameter of the couplers which is 5.77”, the horizontal distance of 3.7” between the guide rods, and the vertical height of 3.4’’ from the top of the R&D sled and the inner surface of the tubes.

For the overall design of the frame of the UAV, the team is aiming for a design that can make use of frame plates as structural components and for housing the electronics. Due to limited space, the UAV frame needs to fit all the electronics in an organized manner to make use of the space as efficiently as possible. The frame is also designed in a way that considers the accessibility of the electronics. The main plates would need to be separated by vertical standoffs to have access to the space in between and to maintain structural integrity. A weighted-decision matrix comparing UAV body configuration options can be seen in the table below.

| DECISION CRITERIA | | BODY CONFIGURATION OPTIONS | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Stacked Plate | | | Hanging Compartments | | | Hanging Pipework | | |
| Required | | Info | | Y/N | Info | | Y/N | Info | | Y/N |
| Size < 6" Width | | 3.8" | | Yes | 3.8" | | Yes | 3.8" | | Yes |
| Length < 10" | | 8" | | Yes | 8" | | Yes | 8" | | Yes |
| Weight < 1 lbm | | 0.75 lbm | | Yes | 0.6 lbm | | Yes | 0.5 lbm | | Yes |
| Wants | Weight | Info | Value | Score | Info | Value | Score | Info | Value | Score |
| Stability | 0.15 | Med | 1.00 | 0.15 | High | 1.50 | 0.23 | High | 1.50 | 0.23 |
| Manufacturing | 0.25 | Med | 2.00 | 0.50 | Easy | 3.00 | 0.75 | Diff. | 1.00 | 0.25 |
| Attachment | 0.25 | High | 1.50 | 0.38 | Med | 1.00 | 0.25 | Med | 1.00 | 0.25 |
| Cost (USD) | 0.15 | 15 | 1.20 | 0.18 | 12 | 1.50 | 0.23 | 18 | 1.00 | 0.15 |
| Accessibility | 0.2 | Low | 1.00 | 0.20 | Med | 2.00 | 0.40 | High | 3.00 | 0.60 |
| Merit | | | | 1.41 | | | 1.85 | | | 1.48 |
| SELECTED CONFIG. | | | | | | | X | | | |

There were many designs considered for the airframe. However, with different airframe designs the rest of the components of the drone would also change. The alternate design consists of four rotation points for each arm, which required more plates than the leading design. It also required more electronic or mechanical systems to make all four arms move to their final locations. The alternate airframe was mainly designed for the compactness of the UAV itself as the four rotating arms would completely fit inside the perimeter of the upper plate. To add more structural integrity between the arms and the rest of the frame, the arms would have two contact points which include a pivot point and a radial slot through which a bolt would slide through as the arms rotated in a circular motion. Aside from that, all of the electronics, including the GPS, would have to be mounted between the upper and the lower airframe plate as opposed to the leading design. Due to complexity and multiple moving parts, this design served as a backup in the end after much consideration.

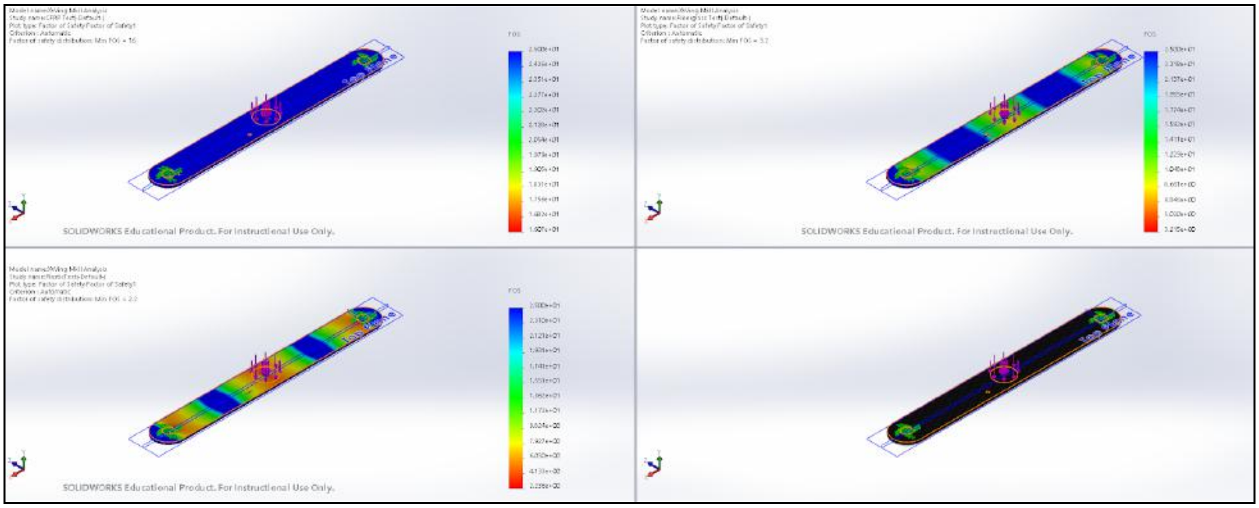
The pipework airframe stemmed from an idea to make the airframe modular in consideration of the electronics. It would be convenient to remove electronic components, work, and replace them securely. It was learned from the team's previous experience building a rover, that more efficient access to electronics was beneficial in speed of fixing or replacing parts. After browsing images of drones, the pipe frame came to fruition and the tray idea was a logical follow up. This design concept can be seen in the figure below.



The trays can slide on and off of the rod. The design also can easily be remodeled to include as many levels of trays as needed. In the image above, a mock ice-mining system is depicted.

#### 4.3.9.2. Material Selection

Three materials were considered for manufacturing of the x-wing arms of the UAV: carbon fiber reinforced polymer composites (CFRP), fiberglass reinforced composites (FRP), and Nylon 6. A static loading analysis was completed on and arm with each of these materials using Solidworks FEA. It is assumed the majority of loads applied in flight are quasi-static since the UAV will not be making aggressive maneuvers and will operate in optimal environmental conditions. Each material is analyzed was run on a single arm with the ends fixed and a load at the center of 40N to capture the maximum expected loading. The results of the FEA simulation can be seen below.



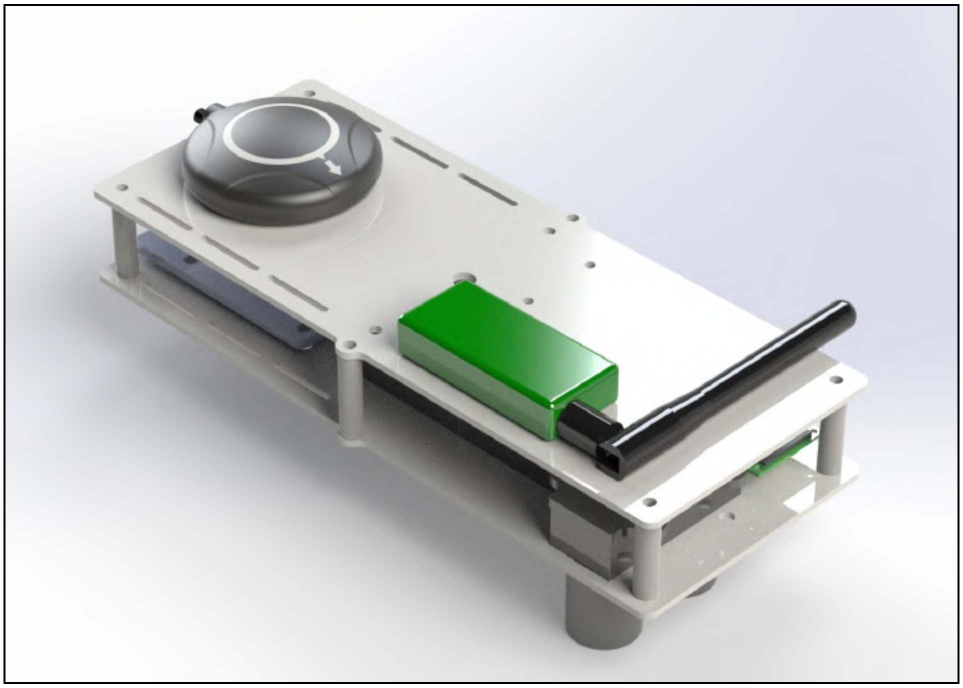

The results of the simulation are CFRP with FOS=16, FRP with a FOS=3.2, and finally Nylon 6 with FOS=2.2. Since the UAV will have two arms sharing the load of the drone, and the lowest FOS for a material was 2.2, any of these materials are of acceptable strength.

Choosing a material then came down to ease of manufacturing, cost, and availability. Nylon 6 is the easiest to machine and has a low price, so it is expected it to have the lowest combined monetary and opportunity cost. Additionally, this allows the team to make multiple parts in case of a fatal UAV crash during testing, making it a lower risk to the project timeline and budget compared to CFRP and FRP.

#### 4.3.9.3. Airframe Design

After considering the limited space and other constraints, the airframe design consists of two horizontal plates, made out of Nylon 6, that are separated by vertical standoffs. It is designed to utilize the space between the guide rods while allowing the drone to take off freely. Through the center of the upper plate is where the the two armatures would be mounted in an x-formation, loaded by a torsion spring. Space between the bottom face of the arm and the upper surface of the upper plate is utilized to mount the telemetry and the GPS module in a compact manner without interfering with any other parts.

A lower plate will be installed about 1.5” below the upper plate and will house the most essential components to the operation of the UAV. In this area, components will be attached to both the top of the lower plate and bottom of the upper plate. In order to structurally connect these two plates, two bolts will be used to attach each of the six vertical standoffs to its respective plate. This will allow the corresponding bolt to be taken off for ease of access to other parts.



Attached to the bottom plate of the UAV is the battery in a housing unit that consists of a much smaller plate and vertical standoffs. To support the landing of the UAV, two sets of legs (one at each corner) will be conformed to fit around the lower plate, attaching them to the bottom plate. These legs will themselves attach to the ice mining system, slung underneath the airframe. In order to produce the required complex shape, a 3D printed model has been proposed. This shape will allow for all of the possible attachment methods to be considered and tested. Nothing will be directly underneath the LIDAR sensor or the camera.

#### 4.3.9.4. Opening Mechanism

In order to allow the propellers to provide adequate lift, they will need to separate from one another as much as possible. Since the internal diameter of the launch vehicle limits the maximum separation distance when the UAV is contained within the R&D system, the propellers will need to be moved into position once released. The system providing this motion may either be active or passive, as the activation of the retention system lifts the UAV's outer constraints.

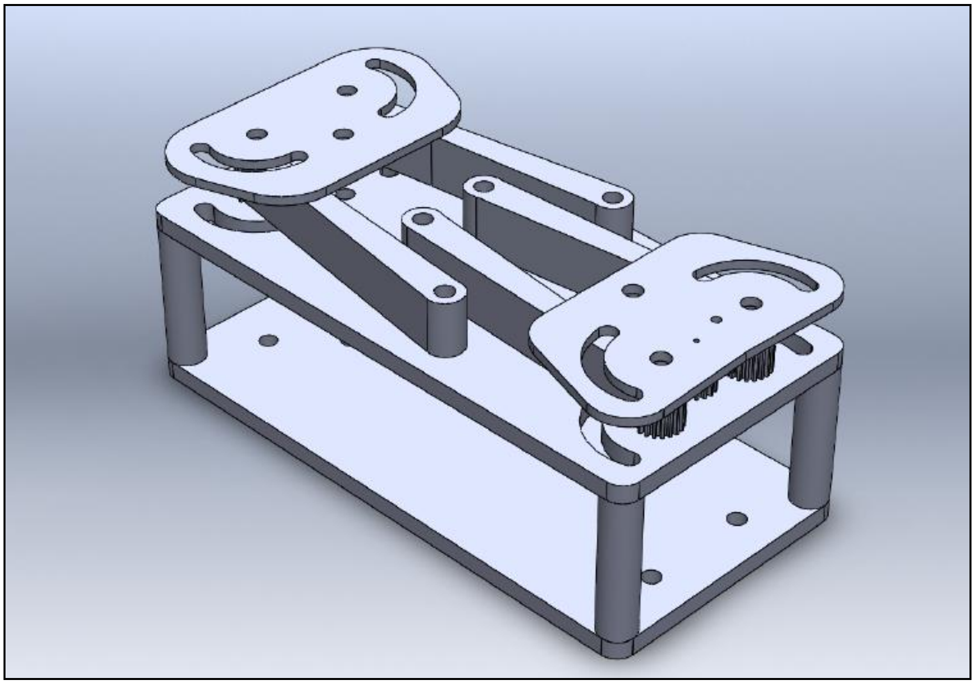
The dimensional boundary of the UAV is required to be contained within the 6" diameter launch vehicle airframe section. With internal components, the UAV will need to be further constrained to approximately 5.77" in diameter. With the height constraints imposed by the sled of the retention system and a 3.7" width constraint between retention system structural rods, the maximum height from the top of the sled to the inner wall of the launch vehicle airframe is about 3.4".

Using these values as a basis, the opening mechanism designs involved methods of folding individual lift unit pylons or armatures. These devices would be actuated into place by a separate controllable unit. Since a single commonly agreed upon design concept was not reached, it was decided to produce multiple approaches to meet the design constraints. A weighted-decision matrix analyzing these approaches is seen below.

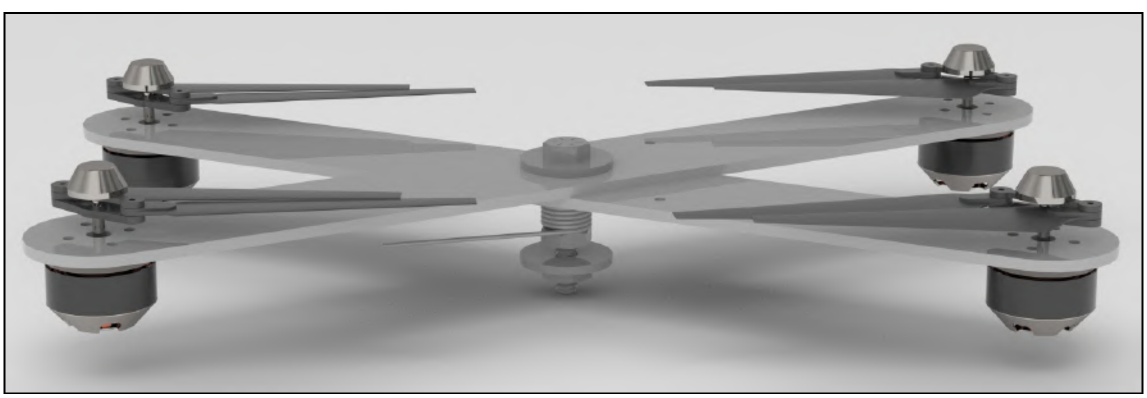
| DECISION CRITERIA | | OPENING MECHANISM OPTIONS | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | XMechanism | | | Quad-Actuation | | | Linear Extension | | |
| Required | | Info | | Y/N | Info | | Y/N | Info | | Y/N |
| Size < 6" Width | | <4" | | Yes | <5" | | Yes | 5" | | Yes |
| Lift Separation > 6" Dist. | | >sqrt(2) * Radius | | Yes | >1/2 * Radius | | Yes | >1/2 * Radius | | Yes |
| Weight < 0.5 lbm | | >0.25 lb | | Yes | >0.4lb | | Yes | >0.5lbm | | Yes |
| Wants | Weight | Info | Value | Score | Info | Value | Score | Info | Value | Score |
| Low Length | 0.35 | 2 * Radius | 1.00 | 0.35 | Radius | 2.00 | 0.70 | Radius | 2.00 | 0.70 |
| Manufacturing | 0.3 | Easy | 3.00 | 0.90 | Diff. | 1.00 | 0.30 | Diff. | 1.00 | 0.30 |
| Cost | 0.2 | Low | 3.00 | 0.60 | Med | 2.00 | 0.40 | High | 1.00 | 0.20 |
| Durability | 0.15 | Med | 2.00 | 0.30 | Med | 2.00 | 0.30 | High | 3.00 | 0.45 |
| Merit | | | | 2.15 | | | 1.70 | | | 1.65 |
| SELECTED METHOD | | | | X | | | | | | |

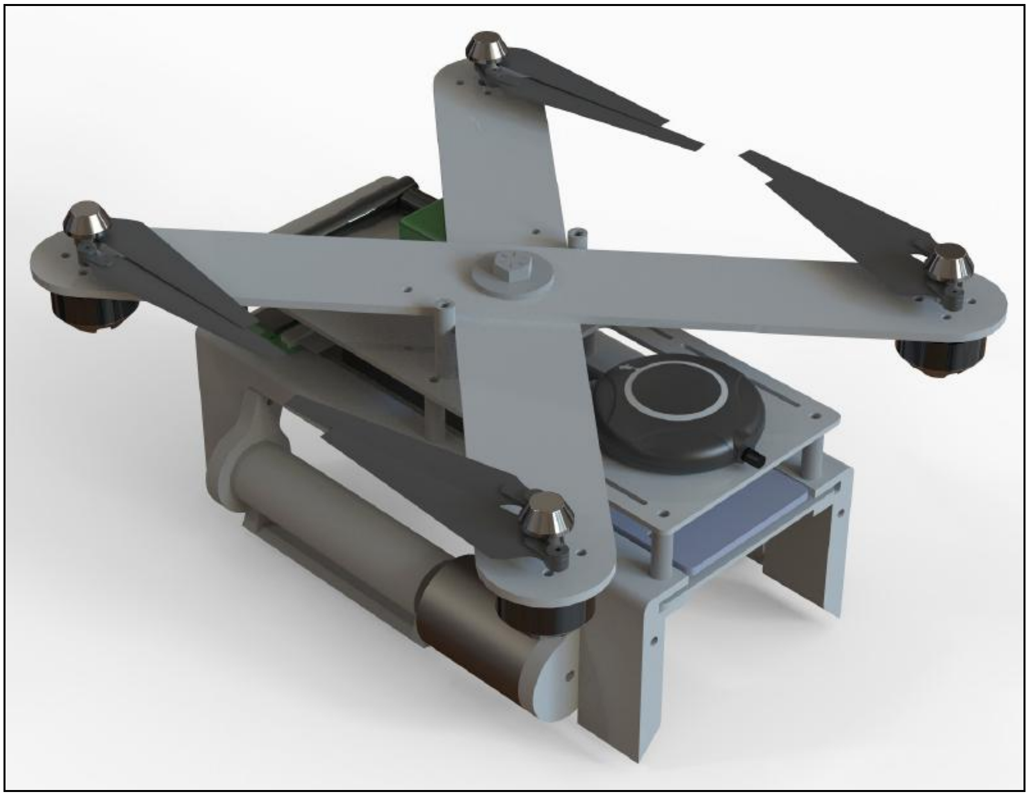
An alternative opening mechanism for the UAV consisted of four separate arms that would be retracted within the frame plate perimeter.  This design is called the Quad-Actuation mechanism. The arms rotate in pairs of two through a small DC motor and a driven gear. This would require the team to manufacture the rotation points of the arms in a manner that resembles a gear so the surface has teeth that fit with the cogs of the driving gear. This design would require two additional motors on a side from the four motors for the propulsion system. Adding those motors would not necessarily draw too much current for the battery but it adds complexity to the UAV in terms of fabrication and assembly, as well as extra weight. Referring to the trade study above, this mechanism would take the least amount of space in the starting position but manufacturing would not be as simple as the XMechanism.

Another proposed alternative would include an actuation system involving actively controlled linear actuators in the form of pneumatic pistons or servos. Upon discussion, it was determined through past experiences with such devices that they would require too much space and weight for the purposes of the UAV. Therefore, it was decided that the final chosen design should minimize the weight and complexity of the design.



The current leading design, seen in the figure below, followed a concept for removing as many moving parts as possible in an effort to lower complexity in manufacturing as well as overall weight. The opening mechanism, referred to as the “XMechanism” includes two 12” overlaid armatures that can rotate about a central axis running through the UAV. At either end of each armature is one of the UAV’ s four lift-producing motor units. While in its closed configuration, the armatures are within 30° of each other, allowing the overall width of the assembly to be minimized under the target 3.7” width. Both armatures are installed with a passive opening actuator in the form of a coaxial torsion spring. This spring will attempt to separate the two armatures to approximately perpendicular configuration, allowing for the lift producing units to maintain a maximum separation distance. In order to provide a stopping point to prevent further rotation, standoffs will be positioned in such a way that further than 90° rotation is prevented.





Inspecting this design, the forces applied during flight are transferred through each individual armature pylon to the central washer and bolt, being further applied at the top of the airframe plate. The main concerns with continuing along with this design is whether its overall closed length, which is slightly less than 12", will be able to properly open once the R&D system deploys. During flight, this system is under frictional constraint with the inner diameter of the launch vehicle airframe. The R&D system is therefore effectively the active mechanism by which the XMechanism deploys. Furthermore, an additional concern is whether the installed torsion spring can apply sufficient torque to open the XMechanism; current estimates assume to use a 3inlbf torsion spring, however this magnitude will be adjusted to fit the needs of the mechanism.

#### 4.3.9.5. Systems Integration

**Electronics**

The airframe must house all of the electronic components required for the operation of the UAV. The total required area for the electronics was reported to the airframe team to be approximately 50 $cm^2$. These components need to be attached via fasteners and ties, requiring the plates to have holes to accommodate both types. In order to fit all of the required parts, the surface area of the bottoms of either plates will be utilized as well. Slots will also be provided to allow for electronics wiring to pass through.

**Retention & Deployment**

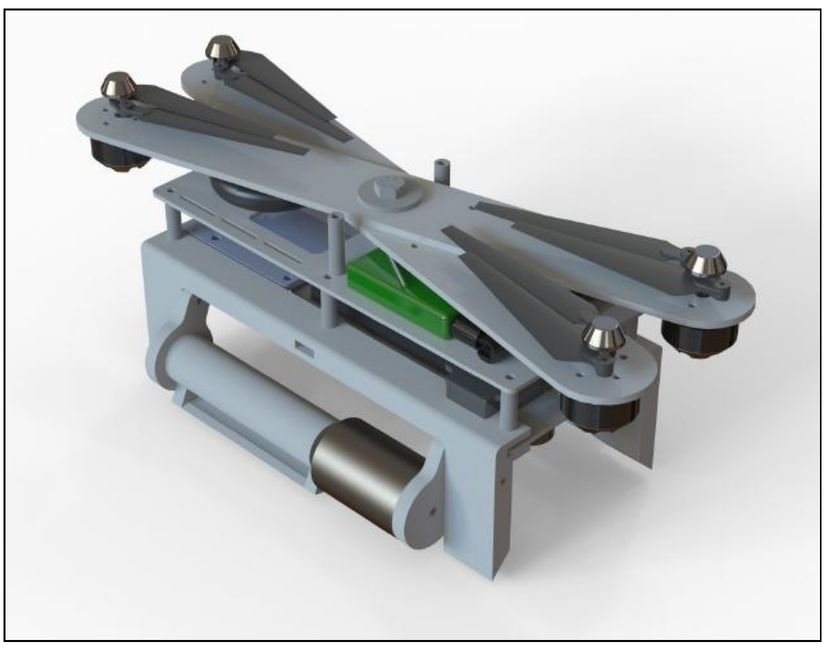
Through a process of iterative design, an airframe design and a retention and deployment process were developed. The proposed method of actively retaining the airframe in the launch vehicle will be via vertical rods that will hold the airframe in place in the plane of the sled. Loops around the legs of the airframe will slip around the rods. The placement of the guide pins is subject to change before CDR. The propeller arms will fit snugly against the inner surface of the launch vehicle to keep the drone from rocking in the vertical direction with respect to the sled orientation.

**Ice Mining**

After total space was determined within the launch vehicle, and after the decision was made about which ice mining system was going to be used, a design and decision had to be made about how the ice mining system would be attached to the drone. The current design is to have the ice mining system (which can be simplified in description as a horizontal cylinder with a diameter of 1.25 in.) be mounted with their own arms to the drone legs on a rotating axis. The purpose of the individual rotation is to be able to use more space within the launch vehicle, but also be able to fit past the guide rods within the launch vehicle when the drone takes off. A torsion spring will be used to help rotation so that the drone does not get stuck. The goal is to have the legs carry the weight of the drone when landed, and then the spring puts a force on the ice mining system so that it can collect a sample of ice.

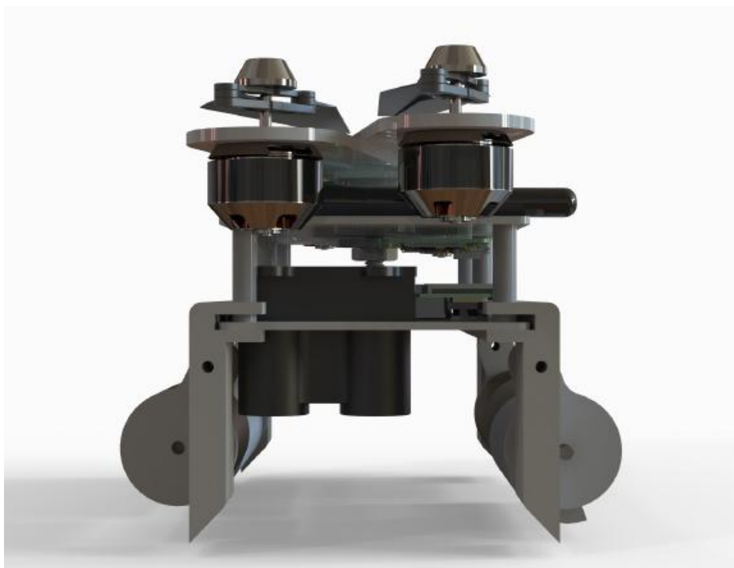
### 4.3.10. UAS Leading Design

The leading design of the UAS is a fully autonomous quad-rotor UAV that is equipped with a set of rotating ice scoops and is supported by a fully integrated GCS. The construction of the UAV utilizes a space-efficient folding x-wing design that enables slender storage in the launch vehicle body when folded, but maximizes propeller blade area when deployed. The pair of x-wing pylons are fixed to the top of the airframe and are passively actuated using a tension spring. The x-wing is fixed atop a set of nylon plates that house the electronics and are separated by a pair of standoffs. This assembly is held up by a pair of 3D printed legs that each integrate its own ice scoop. Seen below is a model of the UAV's preliminary leading design.



The material selected for the majority of the airframe's components sought to minimize weight, cost, and manufacturing difficulty while meeting the expected loads. Nylon 6/6 was the best material that fit these criteria as it is lightweight, cheap, quick and easy to manufacture, and was determined to have enough strength to make the x-wing and the plating. The legs of the UAV are 3D printed to allow for the easy integration of the ice-mining scoop while also allowing for the creation of a contour that would enable easy integration with the retention and deployment system.

In order to minimize the space that the payload occupies in the launch vehicle, the motors are attached below the arms of the x-wing with the motor shaft running through the structure and finally the folding propeller resting on the end of the motor shaft just above the x-wing arms. In order to maximize flight time, the propellers were selected to have a diameter of 7" as this would yield the largest propeller area given the spacing constraints. Seen below is a side-view of the UAV that presents the configuration of the propulsion system with its hanging motors.



The electrical hardware on the UAV enable its autonomous flight, allow for its long-range control, allow for its mission planning capability, and maximize its flight time. At the core of the UAV electronics is the Raspberry Pi Zero MCU and the Pixhawk 4 FCC that handle and process all data on the vehicle and manage any incoming and outgoing communication with the GCS. Communication between the Raspberry Pi Zero and the Pixhawk 4 will be completed through a serial connection using the MAVLink protocol. Flight planning will be completed by the MCU which will make decisions based on imaging data received from the Raspberry Pi Camera and AGL altimeter data. Flight planning setpoint data from the MCU is sent to the FCC and this data is used to control motor outputs. Powering the UAV is the 3600mAh battery that delivers power to all components directly or indirectly through the PDU.

The estimated mass for the leading preliminary design lies just below 2lbm. The weight breakdown can be seen in the table below. Assuming an average thrust-to-weight ratio of 1.5 during operation of the UAV, the maximum effective flight time based on the selected electronics and propulsion system is expected to be 8 minutes.

| Name | Quantity | Weight (oz.) | Total Weight (oz.) |
|---|---|---|---|
| Electronics Plate - Nylon 6 | 1 | 1.02 | 1.02 |
| Top Plate - Plate | 1 | 1.23 | 1.23 |

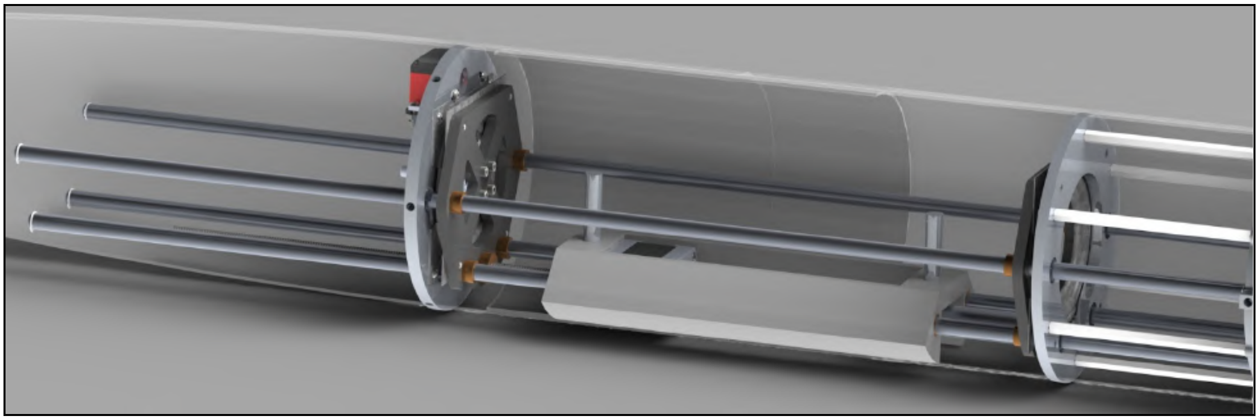
| | | | |
|---|---|---|---|
| XWing Pylon - Nylon 6 | 2 | 0.78 | 1.56 |
| Pixhawk 4 | 1 | 0.56 | 0.56 |
| GPS | 1 | 0.71 | 0.71 |
| SiK 915MHz Telemetry Unit | 1 | 0.35 | 0.35 |
| Raspberry Pi Zero | 1 | 0.32 | 0.32 |
| LiDAR Lite v3 | 1 | 0.78 | 0.78 |
| XSR RC Receiver | 1 | 0.13 | 0.13 |
| PDU Board | 1 | 1.27 | 1.27 |
| Nylon 6 Standoffs | 8 | 0.07 | 0.56 |
| UAV Legs - PLA | 2 | 0.63 | 1.27 |
| Turnigy Aerodrive SK3 1700Kv | 4 | 1.09 | 4.37 |
| Turnigy Multistar 21A | 4 | 0.18 | 0.71 |
| 7xF APC Propeller | 4 | 0.18 | 0.71 |
| FH45mm-6 APC Prop Hub | 4 | 0.35 | 1.41 |
| Turnigy 3600mAh Battery | 1 | 11.32 | 11.32 |
| Airframe Hardware | 1 | 0.71 | 0.71 |
| Airframe Wiring | 1 | 0.71 | 0.71 |
| Geared DC Motor | 2 | 0.71 | 1.41 |
| Scoop - PLA | 2 | 0.35 | 0.71 |
| **Total Weight** | | | **31.82** |

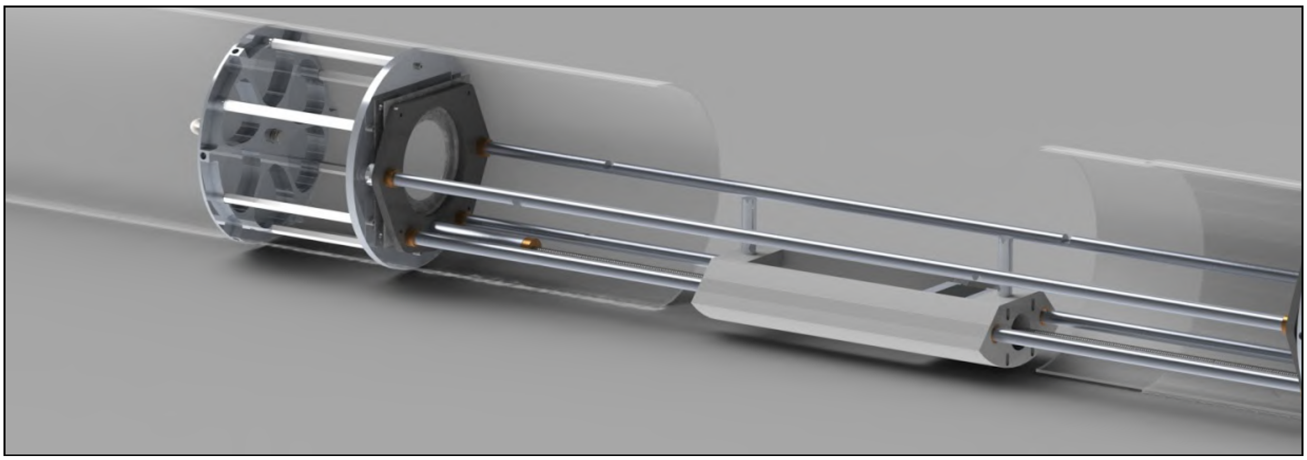
## 4.4. Selection, Design, and Rationale of Retention and Deployment

The R&D system must prevent motion of the UAV payload during flight, reorient the payload after landing, allow the UAV to exit the craft after landing, and not compromise the overall integrity of the launch vehicle.

### 4.4.1. Retention and Deployment Subsystem Overview

The R&D system is comprised of the payload retention system, the sled deployment system, the payload orientation system, and the R&D electronics system. These systems work together to safely hold the UAV payload within the launch vehicle throughout the course of the flight and to facilitate a successful deployment of the UAV after landing. The figures below show the R&D system in both its open and closed configurations (respectively).





The structural integrity of this system, both internally and with respect to the rest of the launch vehicle, has been a major factor in the design of this system and is discussed further in the sections below. Further details on each of the aforementioned R&D subsystems, as well as the electronic control of these systems, is seen below as well.

### 4.4.2. Payload Retention System

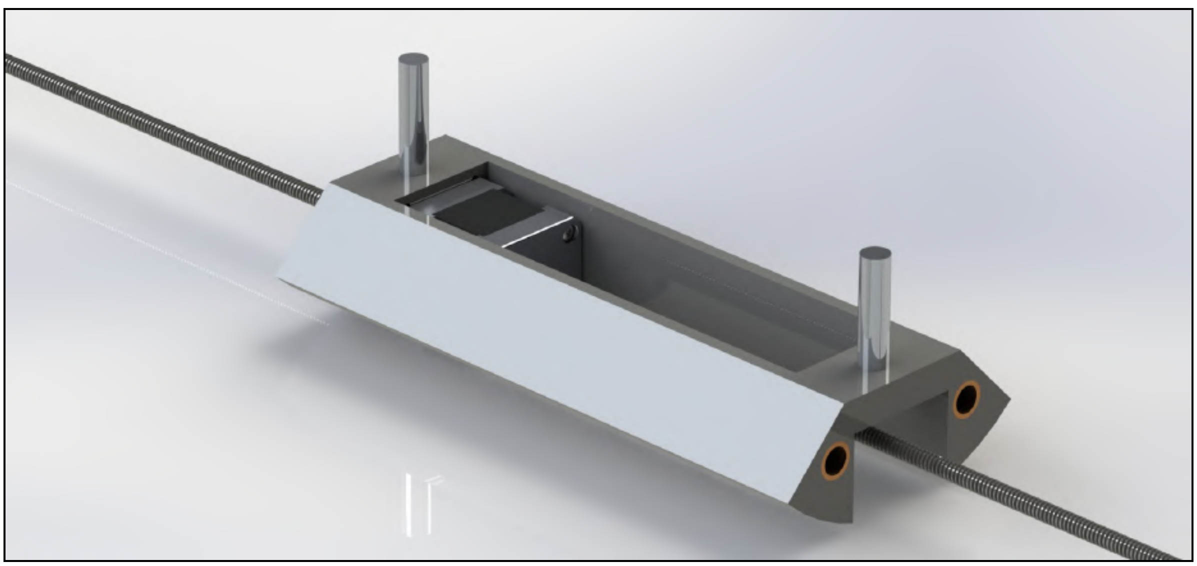
There are many options to retain the payload within the bay, including both passive and active systems. The leading choice is a guide rod system along with a clipping mount to the payload sled. There will be two guide rods separated by a half-inch less than the length of the drone. These rods will be rigidly attached normal to the top surface of the payload sled and the UAS will slide onto the rods, restricting its movement in the 2 horizontal axes. The last vertical axis will be restricted by an attachment clipping system where the drone's legs clip onto the sled. As a secondary safety measure, the drone will be unable to slide off of the guide rods while the payload bay is closed. This will allow for the safe retention of the UAV while also allowing for the smooth deployment of the UAS once the bay is open.

| Criteria | Weight | Passive Guide Rods | | Active Clamping System | | Passive Clipping System | |
|---|---|---|---|---|---|---|---|
| | | Rating | Score | Rating | Score | Rating | Score |
| Cost | 2 | .8 | 1.6 | .4 | 0.8 | 1 | 2.0 |
| Complexity | 3 | 1 | 3.0 | .6 | 1.8 | .4 | 1.2 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Safety | 5 | .8 | 4.0 | 1 | 5.0 | .4 | 2.0 |
| Practicality | 3 | .6 | 1.8 | .6 | 1.8 | .4 | 1.2 |
| Weight | 4 | 1 | 4.0 | .8 | 3.2 | 1 | 4 |
| Total Score | 17 | | 14.4 | | 12.6 | | 10.4 |

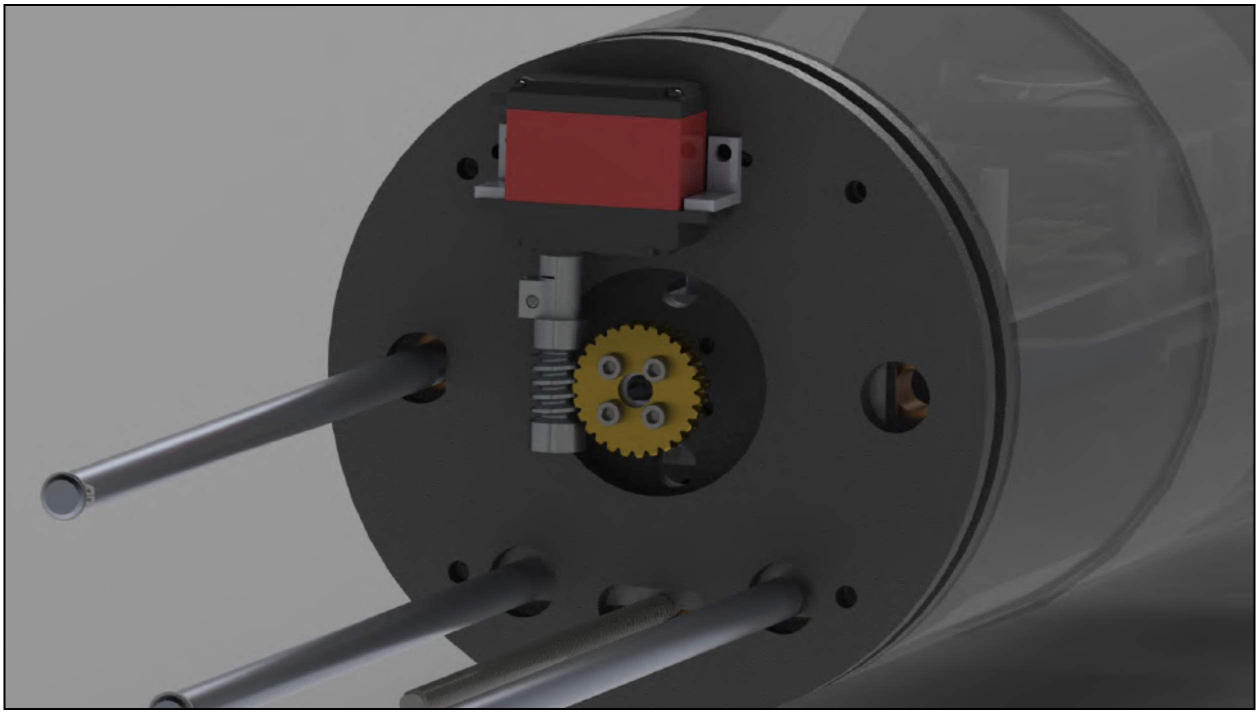
### 4.4.3. Sled Deployment System

With the use of a UAV payload it must have a stable platform from which it can easily take off while also being immobile during the launch vehicle ascent and descent phases. Two leading designs were developed for deploying the UAV from the launch vehicle. The first is the barn door method which consists of two doors that are also sections of the airframe opening and exposing the payload. The payload would then take off from an internal platform, negating the use of a sled. Due to the difficulty of manufacturing and concerns with the structural integrity of the launch vehicle being affected, it was decided not to use this method. The second method considered uses a motor and lead screw to push the nose cone off from the main body of the launch vehicle revealing a sled carrying the payload. The sled will be structurally attached to two rods that will be extendable after flight to successfully launch the payload. The sled and payload will be fixed in place with notches and non-backdrivable worm screws during the launch vehicle's flight so that it does not move or swing causing instability of the launch vehicle and potential damage to the payload itself. The sled will also provide attachment points from which the UAV will be able to keep itself secure during flight. After the launch vehicle successfully lands, the sled will rotate using a continuous servo allowing it to orient itself until the sled and UAV are pointed vertically. After the system orients itself the UAV will detach from the sled and ascend completing its mission. An image of the sled assembly is seen in the figure below.



### 4.4.4. Payload Orientation System

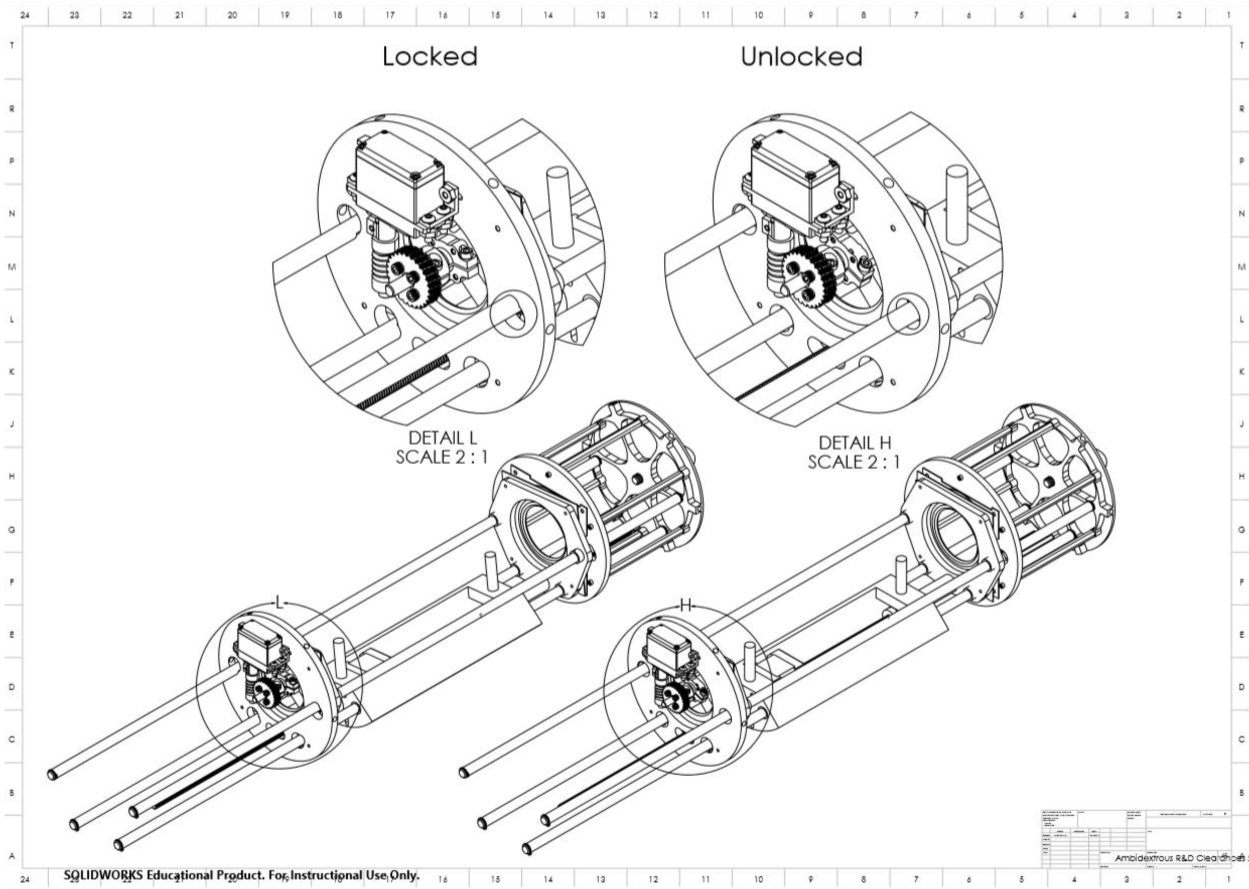
The use of a UAV payload presents orientation as an additional problem that must be solved for deployment to be successful. Even if the payload had a clear egress method from the launch vehicle, if it is improperly oriented it will be unable to take off and perform its objectives. The first design considered for orientation was a passive “Swing” type system. This would consist of the payload sled being mounted with a bearing on each side, enabling the sled to passively rotate to the upright position once the launch vehicle has landed and opened up. The other option that was considered was very similar, but used a motor to orient the sled upon landing. This motorized design was eventually chosen as it gives more control over the way the payload deploys. This motor uses a 6-DOF IMU located in the payload bay to find the correct orientation. The figure below depicts the payload orientation system.



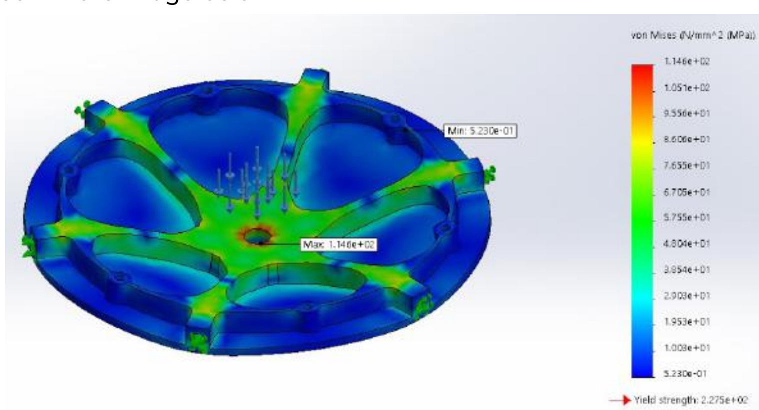
### 4.4.5. Structural and Recovery Interfaces

Along with strongly retaining the payload, the chosen system must also interface with the recovery system while not compromise the strength of the launch vehicle. This took different forms for each method of deployment that was considered. For a “Hinged Doors” method, the integrity takes the form of ensuring that the launch vehicle can still handle the stresses of flight while having a large amount of material removed from the primary structural element (the fiberglass body tube). For the chosen “Opening sled” design, the system must hold the nose cone firmly on the launch vehicle during flight and landing. The simplest way to ensure that no components of the R&D system move during launch is to have all the motors provide stall torque before and during flight. While this would provide retention equal to the torque of all the motors, the design was eliminated as it would draw power at all times and would not be considered fail-safe. This would necessitate large batteries in the launch vehicle which were deemed to be unnecessary weight. The more efficient solution to this problem is to use a non-backdrivable rotation system which can lock into detents in the linear rods. This retention prevents axial motion by using axial rotation. The perpendicularity of this system ensures that the nose cone is held on with force equal to yield strength of the rotary plates.

Any chosen structural system will be verified using FEA and have FOS>=2.0. This system is detailed in the figure below.




The bulkplate at the aft end of the system also acts as the attachment point for the main parachute, so it must be able to handle substantial loads during main deploy. Using FEA in solidworks, the weight of the plate has been optimized while maintaining a FOS >2 assuming a maximum loading of 1000lbf. Results of this analysis are seen in the image below.

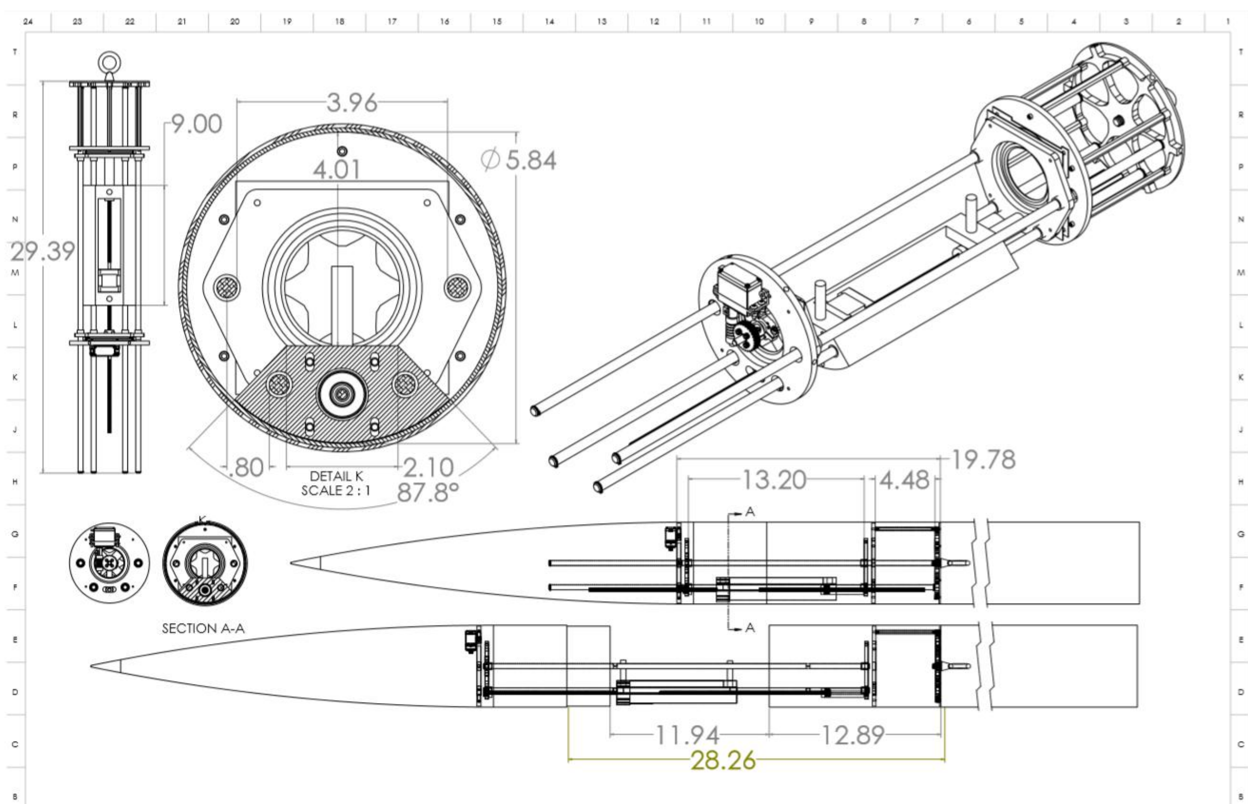



### 4.4.6. Leading R&D Mechanical Design

The leading mechanical design consists of the most optimal designs for each of the aforementioned subassemblies of the R&D system. The system is anchored to the main body tube of the launch vehicle by an aluminum bulkplate, which serves 2 purposes on top of its structural value for R&D . First, it gives the main parachute a place to attach to the body of the launch vehicle via an eyebolt, it also prevents hot gasses from the parachute ejection charges from damaging the payload or R&D. 6 aluminum standoffs connect this aluminum plate to the lower stationary pass through plate, which provides a mount for a turntable, as well as a surface into which the guide rail notches can lock onto during flight.

Attached to the turntable is the sled swing. This assembly provides a mount for the payload and power to expand the payload bay. The payload interfaces with the sled through vertical shafts, and guide rods attached to the rotary pass through plates. This constrains axial and radial motions throughout flight. Contained within the sled is a Nema 17 stepper motor, which provides power to a left handed lead screw in the front, linked to the upper rotary pass through plate, and a right handed lead screw connected to the lower rotary pass through plate. These opposing lead screws create forces that push both the upper and lower pass through plates away from the sled. Since the body of the launch vehicle experiences high frictional forces, these forces are realized as the sled moves away from the body, and the nose cone region moves twice as far as the sled, creating a large opening for egress. Once this is opened, the guide rods will be completely free from the stationary pass through plates, allowing the sled swing to rotate through 360 degrees of motion in order to right the payload.

This rotation is achieved through a servo and worm gear assembly mounted in the nose cone. The already strong servo is given an additional 27x torque increase through a worm gear system, allowing it to power through any internal contact due to misalignment of other systems. The worm gear system also prevents the sled from being backdriven at any time during flight, allowing the detent notches to be trusted with the role of holding the nose cone firmly in rotation and translation throughout flight. The control and powering of this servo is addressed in the following electronics sections.



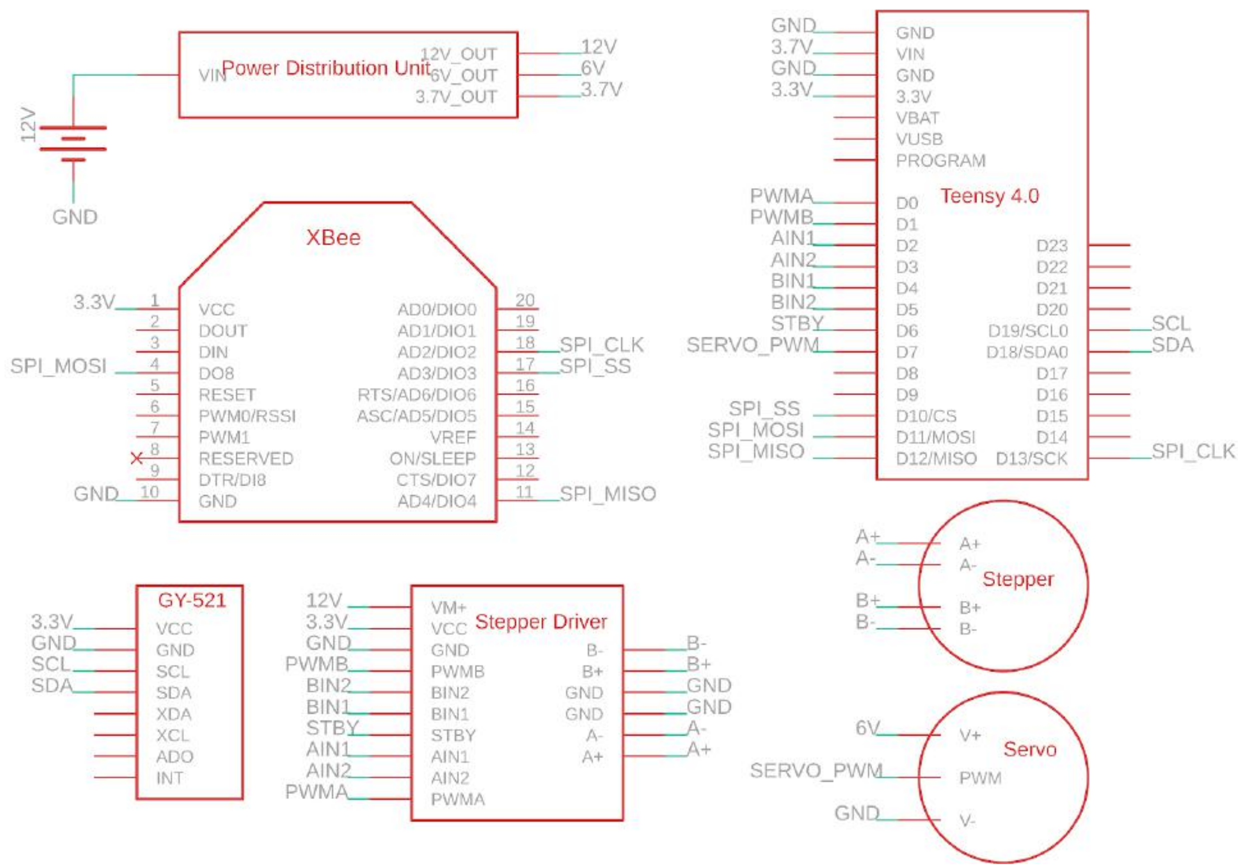
### 4.4.7. Communication and Data Links

Selection of an RF module was based on price, associated risk, ease-of-use, power draw, and range. The XBee-PRO 900 HP DigiMesh Kit is priced within the payload team's budget at $99 and includes all necessary communication functionality. The kit has a cost delta of $10 compared to buying two modules, however it includes three RF modules plus extra tools, thus justifying the higher price. The kit manufacturer provides high rate consumer product components, so the team expects high quality (Cpk=1.33), thus reducing the risk to timeline and project budget. The modules in the kit are also highly documented, which allows for easy interfacing with retention and deployment electronics. At a max power consumption of 290mA@3.3VDC for the highest power level, the modules can provide 4mi LOS range.

The XBee shall interface with an arduino-based Teensy 4.0 microcontroller via SPI serial connections. While the XBee can be programed to control devices such as a servo directly, it is believed that interfacing to a much more familiar arduino platform represents a lower risk to the anticipated timeline. The Teensy 4.0, compared to an arduino nano, is about the same size, about the same price, and is orders of magnitude faster with many more features. While the board consumes about 100mA at 600MHz, it supports dynamic clock scaling (as well as manual underclocking and overclocking) without affecting serial BAUD rates, which will allow for power savings. The high performance of this microcontroller makes it a great futureproof choice, as it has the capability to do much more than control motors if necessary. In addition to these benefits, the Teensy 4.0 streamlines the power distribution setup, which will be explained more in the Batteries and Power Distribution Section.

The Teensy will control the Double Shaft Nema 17 Stepper Motor via the Adafruit TB6612 1.2A DC/Stepper Motor Driver Breakout Board, and control the HSR-2648CR Servo directly.

The payload retention and deployment system will contain one Teensy 4.0, one XBee RF module, and one stepper driver. The The GCS will communicate with the payload retention and deployment system via it's own Teensy 4.0/XBee RF system. The schematic of the R&D electronics can be seen in the figure below.




### 4.4.8. Batteries and Power Distribution

The retention and deployment system controller subsystem shall be powered by a Lithium Ion battery due to superior energy density and weight characteristics compared to alternatives. All of the following sizing calculations were done assuming the electronics on the launch vehicle are powered for longer than expected and a FOS was added to account for the combined inefficiencies in voltage conversion, small IO currents, sleep currents, etc.

One benefit of the Teensy 4.0 is that it has a 3.3V regulated output that can output up to 250mA, which means it can constantly power the XBee directly at the second highest power setting (the second highest power setting is 160mA typical, and the highest is 215mA typical 290mA max). All other connections to the Teensy are IO, which will draw negligible currents that are grouped together as a FOS of 1.5. In calculating the energy needed for the electronics, the team assumes the Teensy draws 100mA the whole time and the XBee will be drawing 290mA the whole time. Therefore the energy needed for the controller subsystem is:

$$(100mA+290mA) * 2hrs * 1.5FOS = 1170mAh$$

The orientation servo runs at 4.8-7.4V but does not spec a current, so the team will assume high current at 1A for battery sizing. The team will assume the servo will run for 2 min for each rotation, to be plentiful with battery sizing. The team will account for two rotations, one when locking the bay closed, and one when unlocking/orienting the bay. Therefore the energy needed for the servo is:

*(1000mA) * 2 * 2/60hrs * 1.5FOS = 100mAh*

The expansion stepper driver runs at up to 1.2A at 12V. The team will assume the stepper will run for 2 min for a single expansion/contraction of the bay. The team will account for two movements, one when closing the bay before launch, and one when opening the bay after launch. The team will also include the FOS of 1.5. Therefore the energy needed for the stepper is:

*(1200mA) * 2 * 2/60hrs *1.5FOS = 120mAh*

The total energy needed is therefore 1170+100+120mAh = 1390mAh. With this energy requirement in mind, and the fact that converting to a lower voltage is much more efficient than converting to a higher voltage, one 12V battery will power the entire R&D system through a power distribution system. The battery chosen is the ABENIC DC 12V 2A (24W) 1800mAh Super Rechargeable Portable Li-ion Lithium Battery DC168. This battery will be connected to a power distribution system that outputs at multiple voltage levels. As the highest electrical component requires 12V, no device will require converting to a higher supply voltage.

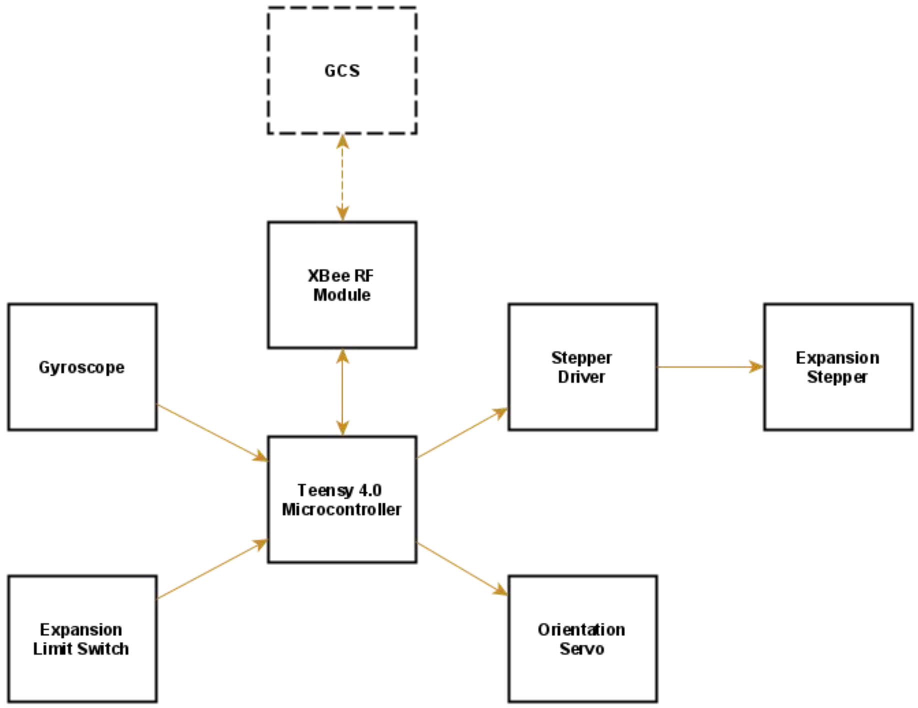
### 4.4.9. Leading Electrical Design

The Teensy 4.0 will send and receive data with the GCS via the XBee RF modules in the GCS and payload bay.

The Teensy will receive a signal from the GCS to begin the orientation procedure. The Teensy will get orientation of the bay from a mounted gyroscope and send a signal directly to the orientation servo to control position through a simple feedback system. The Teensy will send the orientation back to the GCS.

The Teensy will receive a signal from the GCS to expand the payload bay. The Teensy will then control the expansion stepper motor via a driver board. The wires from the driver board to the stepper will need to be long enough for a fully expanded bay, so there will be multiple folded links of stranded wire so the wires can become longer as the bay expands.

A PCB will contain the Teensy 4.0, XBee, stepper driver, gyroscope, and a power distribution system to power everything in the R&D section. This PCB is will be sent to a PCB fabrication house after validating the design of the R&D electronics in prototype form. A block diagram depicting the overall electrical design of the R&D system is seen in the figure below.

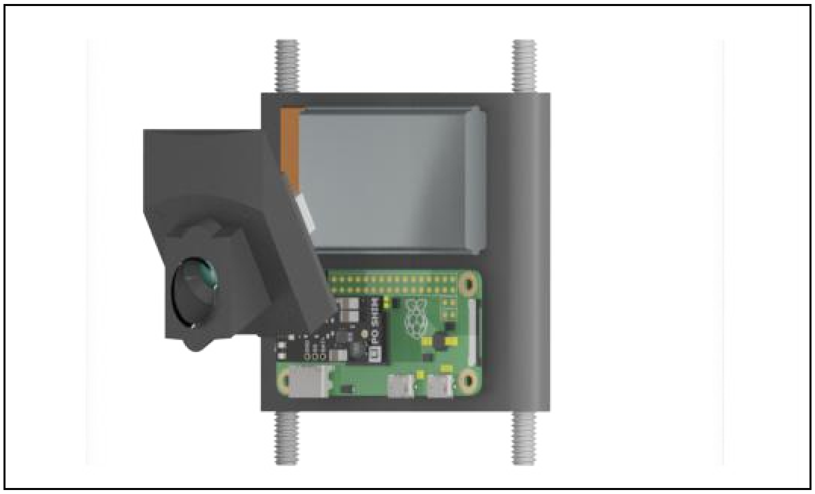



## 4.5. Camera Module Secondary Payload

In addition to the UAV payload, a secondary high-resolution camera payload will be integrated into the launch vehicle that will record during launch vehicle ascent and recovery. The recordings of these cameras will be used to expand the team's social media presence as well as observe the flight trajectory from the point of view of the launch vehicle.

### 4.5.1. Camera Module Design

The camera module will be installed inside the avionics bay, but will function independently from the recovery system. The camera module will be a single 13MP 4k camera pointing 30° downward from the horizontal connected to Raspberry Pi Zero (RPiZ) through a USB connection. The camera will be mounted internally directly along the inner diameter of the avionics bay using a 3D printed mount. The RPiZ will be poweredwill be fixed to a sled that is mounted to a set of all-threads running inside the avionics bay. Recording will be controlled by a push button toggle switch and its status will be displayed by a set of LEDs. The estimated total weight of the system is 0.4lbf. The preliminary design of the camera module can be found in the model below.




Other designs considered included a set of four outward facing GoPro cameras that would combine the imaging data to form a 360° panoramic video and another similar design using a pair of RPi 4 computers each with their own pair of cameras. Due to concerns of weight and space, the current leading design is the lightest and smallest option that makes use of a single camera. If it is determined that extra weight can be allocated for the camera bay, another camera may be implemented that would be mounted on the opposite side of the avionics bay.

# 5. Safety

## 5.1. Hazard Analysis Methods

Critical to the success of any mission is a comprehensive understanding of the dangers involved therein. Threats to personnel, environmental factors, project dangers, and launch vehicle failure modes all contribute to the cumulative risk associated with the mission. While each team takes careful steps to minimize any such risks, and to not put team members in harm's way, the danger associated with missions such as these will likely never be fully abated. Acknowledgement of these dangers, and a thorough plan for their mitigation, is the only way to guarantee the safety of the team, and to maximize the likelihood of mission success.

For the purposes of this mission, risk analysis was broken into two categories: event probability and event severity. The respective definitions of these categories are listed below.

| Category | Value | Gauge |
|---|---|---|
| **Remote** | 1 | Less than 3% chance of event |
| **Unlikely** | 2 | 3-10% chance of event |
| **Possible** | 3 | 10-25% chance of event |
| **Probable** | 4 | 25-50% chance of event |
| **Likely** | 5 | Greater than 50% chance of event |

In the consideration of severity, the team established several metrics for defining the associated levels, key among them being reversibility and remediation time. The highest level of severity corresponds to total irreversibility of the damage done; in various contexts, this may mean loss of life or permanent function, permanent environmental damage, or a complete scrub of the mission. Lower levels of severity are characterized by long term reversibility, and further delineated by the length of said remediation, ranging from an on-the-spot solution (first aid, consumable tool replacement, small leaks or spills) to the need for external assistance or long recovery (hospitalization, machine repair, primary environmental restoration).

| Category | Value | Health and Personal Safety | Equipment | Environment | Flight Readiness |
|---|---|---|---|---|---|
| **Negligible** | 1 | Negligible injury. No first aid required. No recovery time needed. | Minimal and negligible damage to equipment or facility. No required correction. | Negligible damage. No repair or recovery needed. | No flight readiness disruption. |
| **Minor** | 2 | Minor injury. Requires band-aid or | Minor damage. Consumable | Minor environmental impact. Damage is focused on a | Flight proceeds |

| | | | | | |
|---|---|---|---|---|---|
| | | less to treat. 5-10 minutes of recovery time required. | equipment element requires repair. | small area. Little to no repair or recovery needed. Outside assistance not required. | with caution. |
| **Moderate** | 3 | Moderate injury. Gauze or wrapping required. Recovery time up to one day. | Reversible equipment failure. Non-consumable element requires repair. Outside assistance not required. | Reversible environmental damage. Personal injuries unlikely. Outside assistance recommended. Able to be contained within team. | Flight delayed until effects are reversed. |
| **Major** | 4 | Serious injury. Hospital visit required. No permanent loss of function to any body part. | Total machine failure. Outside assistance required to repair. | Serious but reversible environmental damage. Outside assistance required. Personal injuries possible. | Flight on hold until system is removed. |
| **Disastrous** | 5 | Life threatening or debilitating injury. Immediate hospital visit required. Permanent deformation or loss of bodily function. | Irreversible failure. Total machine loss. New equipment required. | Serious irreversible environmental damage. Personal injuries likely. Immediate outside assistance required. Area must be vacated. Need to be reported to relevant agency. | Flight scrubbed or completely destroyed. |

In the consideration of these definitions, the team focused on establishing quantitative metrics for each level of probability and severity. The establishment of measurable standards for these categories enables the team to accurately assess the risk of every considered event (listed in the following sections). Cumulative risk for each event is found by a cross examination of the likelihood and severity of each event (performed in this case by the multiplication of the assigned values in each of these categories). A table demonstrating this is given below. The color code displayed is as follows:

- Green: Minimal risk
- Yellow: Low risk
- Orange: Medium risk
- Light red: High risk
- Dark red: Very high risk

Any event categorized as 'low' or 'negligible' risks are considered acceptable by the team's standards.

| Category | Negligible | Minor | Moderate | Major | Disastrous |
|---|---|---|---|---|---|
| **Remote** | 1 | 2 | 3 | 4 | 5 |
| **Unlikely** | 2 | 4 | 6 | 8 | 10 |
| **Possible** | 3 | 6 | 9 | 12 | 15 |
| **Probable** | 4 | 8 | 12 | 16 | 20 |
| **Likely** | 5 | 10 | 15 | 20 | 25 |

Prior to a plan for risk mitigation, many of the events listed below fall outside of the acceptable tolerance. Listed alongside these events are the team's risk mitigation plans, as well as verification metrics to ensure team compliance. Post-mitigation risk is also listed, ensuring all project risks are within acceptable tolerance.

## 5.2. Personnel Hazard Analysis

| Hazard | Likelihood (Cause) | Severity (Effect) | Risk | Mitigation | Verification | Post Mitigation Risk |
|---|---|---|---|---|---|---|
| Burns From Motor | 2 (Proximity To Launch Pad, touching engine too soon after launch) | 3 (Mild To Moderate Burns) | 6, Low | Maintain minimum safe launch distances. Wait an appropriate amount of time after launch to retrieve. | 200 feet border will be established after mounting of launch vehicle onto launcher as compliance to NAR safety standards. | 3, Low |
| Contact with Airborne Chemical Debris | 3 (Airborne particulate debris) | 2 (Minor burns, abrasions) | 6, Low | Wear appropriate PPE such as gloves,lab coats and breath masks, wash with water. | Safety Team will verify with each participating member that appropriate PPE is worn. | 4. Low |
| Dehydration | 3 (Failure to drink adequate amounts of water) | 3 (Exhaustion and possible hospitalization) | 9, Medium | Ensure all members have access to water at launch. | Mandatory water breaks will be held every hour where no work may be done during that period. | 3, Low |
| Direct Contact with Hazardous Chemicals | 3 (Chemical spills, improper use of chemicals) | 3 (Moderate burns, abrasions) | 9, Medium | Wear appropriate PPE such as gloves or lab coats, wash with water. | Safety Team will verify with each participating member that appropriate PPE is worn. | 6, Low |
| Dust or Chemical Inhalation | 3 (Airborne particulate debris) | 3 (Short to long-term respiratory damage) | 9, Medium | Wear appropriate PPE or respirator, work in a well ventilated area. | Safety Team will verify with each participating member that appropriate PPE is worn. | 6, Low |
| Electrocution | 2 (Improper use of equipment, static | 4 (Possible explosion, destruction of electrical tools | 8, Medium | Give labels to all high voltage equipment warning of their danger; ground | Guaranty no open electrical components. Allow only one member to | 4, Low |

| | | | | | | |
|---|---|---|---|---|---|---|
| | build-up) | or components, possible severe harm to personnel) | | oneself when working with high-voltage equipment. | work on electrical components at a time with proper PPE and student supervising. | |
| Entanglement with Construction Machines | 4 (Loose hair, clothing, or jewelry) | 5 (Severe injury, death) | 20, High | Secure loose hair, clothing, and jewelry; wear appropriate PPE. | No contact allowed without call out before use to make sure PPE is worn. Make sure rules followed as set forth by machining rules. | 5, Low |
| Epoxy Contact | 3 (Resin Spill) | 3 (Exposure to Irritant) | 9, Medium | Wear appropriate PPE such as gloves or lab coats, wash with water. | No contact allowed without call out before use to make sure PPE worn. | 6, Low |
| Eye Irritation | 3 (Airborne particulate debris) | 2 (Temporary eye irritation) | 6, Low | Wear appropriate PPE or protective eyewear, wash with water. | Guaranty PPE worn at all times during manufacturing. Call out before use to make sure PPE is worn. | 4, Low |
| Heatstroke | 3 (High temperatures on launch day) | 3 (Exhaustion and possible hospitalization) | 9, Medium | Wear clothing appropriate to the weather, ensure all members have access to water at launch. | Team members must have adequate clothing, safety team will report violators to the project lead to decide if the violator should be dismissed to a colder area; water will be provided. | 3, Low |
| Hearing Damage | 4 (Close proximity to loud noises) | 3 (Long term hearing loss) | 12, Medium | Wear appropriate PPE such as ear muffs when using power tools. | PPE equipment check must be done by a safety team member before conducting construction. | 6, Low |
| Hypothermia | 3 (Low temperatures on launch day) | 3 (Sickness and possible hospitalization) | 9, Medium | Wear clothing appropriate to the weather, ensure all members have access to a warm area to rest at launch. | Team members must have adequate clothing, Safety team will report violators to the project lead to decide if the | 6, Low |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | | violator should be dismissed to a warmer area. | |
| Kinetic Damage to Personnel | 2 (Failure to take appropriate care around unburned fuel, post-landing launch vehicle explosion) | 5 (Possible severe kinetic damage to personnel) | 10, Medium | Extinguish any fires before recovering, wait for motors to burn fully before recovering, wear appropriate PPE when recovering. | Make sure the area is evacuated and designated individuals are to recover components at a designated time when determined to be safe; no contact allowed without call out before use to make sure PPE worn. | 5, Low |
| Launch Pad Fire | 2 (Dry Launch Area) | 3 (Moderate Burns) | 6, Low | Have fire suppression systems nearby and use a protective ground tarp. | Make sure the area is evacuated and designated individuals are to recover components at a designated time when determined to be safe; no contact allowed without call out before use to make sure PPE worn. | 3, Low |
| Injury from Ballistic Trajectory | 3 (Recovery System Failure) | 5 (Severe Injury, Death) | 15, High | Keep all eyes on the launch vehicle and call "heads up" if needed<br>Limit number of people at launch. | Go through safety procedures before the launch occurs. Emphasize importance of keeping eyes on the launch vehicle during flight. | 5, Low |
| Injury from Falling Components | 3 (Failure to keep all components securely attached to the launch vehicle; result of improper staging constraints, part failure, or excessive | 5 (Severe injury, death) | 15, High | Keep eyes on the launch vehicle at all times; make sure all team members who cannot watch the launch vehicle have spotters nearby; alert others if the launch vehicle enters a ballistic trajectory. | Go through safety procedures before the launch occurs. Emphasize importance of keeping eyes on the launch vehicle during flight. | 5, Low |

| | | | | | | |
|---|---|---|---|---|---|---|
| | vibration) | | | | | |
| Injury from Navigating Difficult Terrain | 2 (Uneven ground, poisonous plants, fast-moving water) | 4 (Broken bones, infections, drowning, etc.) | 8, Medium | Do not attempt to recover the launch vehicle from atypically dangerous areas. | Set boundaries to not cross at the launch location before the launch occurs. | 4, Low |
| Injury from Projectiles Caused by Jetblast | 2 (Failure to properly clean launchpad, failure to stand an appropriate distance from the launch vehicle during launch) | 3 (Moderate injury to personnel) | 6, Low | Clean the launchpad before use, ensure all members are wearing proper PPE for launch, ensure all team members are an appropriate distance from the launch vehicle when launching. | Verify that the launchpad is clean and clear of debris before launch occurs. Create launch checklist to be completed before the launch vehicle can be launched. | 3, Low |
| Physical Contact With Heat Sources | 3 (Contact with launch vehicle parts which were recently worked with, improper use of soldering iron or other construction tools) | 3 (Moderate to severe burns) | 9, Medium | Wear appropriate PPE, turn off all construction tools when not in use, be aware of the safety hazard that parts which were recently worked with present. | Confirm that appropriate PPE is being used. Make sure that everybody is informed of the hazard. | 3, Low |
| Physical Contact with Falling Construction Tools or Materials | 3 (Materials which were not returned to a safe location after use) | 5 (Bruising, cuts, lacerations, possible severe physical injury) | 15, High | Brief personnel on proper clean-up procedures, wear shoes that cover the toes. | Clean workspace every time after use. Create a checklist of where to put items after use. | 5, Low |
| Premature Ignition | 2 (Short Circuit) | 2 (Mild Burns) | 4, Low | Prepare energetic devices only immediately prior to flight. | Place previously used materials in separate container than the unused materials. | 2, Minimal |
| Power Lines | 2 (Launch vehicle Becomes Entangled In Lines) | 5 (Fatal Electrocution) | 10, Medium | Call the power company and stand clear until proper personnel arrive. | Alert all team members of the hazard. Everybody is required to stand clear of the area until certified personal clean up and verify that the | 5, Low |

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| | | | | | area is safe. | |
| Power Tool Cuts, Lacerations, and Injuries | 3 (Carelessness) | 4 (Possible Hospitalization ) | 12, Medium | Secure loose hair, clothing, and jewelry; wear appropriate PPE; brief personnel on proper construction procedures. | No contact allowed without call out before use to make sure PPE worn. Make sure rules followed as set forth by machining rules. | 4, Low |
| Injuries from Quadcopter payload | 2 (Injury from spinning rotors) | 2 (Minor cuts) | 4, Low | Stay clear of quadcopter while it is in operation. Only team members familiar with the payload will handle it. | Stay minimum safe distance at launch and remain at that distance until payload and other components have landed. Have member of payload team retrieve the quadcopter. | 2, Minimal |
| Tripping Hazards | 3 (Materials which were not returned to a safe location after use, loose cords on or above the ground during construction processes) | 3 (Bruising, abrasions, possible severe harm if tripping into construction equipment) | 9, Medium | Brief personnel on proper clean-up procedures, tape loose cords or wires to the ground if they must cross a path which is used by personnel. | Have a clean up sheet for work space occupants to confirm everything is placed where it should be. | 6, Low |
| Unintended Black Powder Ignition | 3 (Accidental exposure to flame or sufficient electric charge) | 5 (Possible severe hearing damage or other personal injury) | 15, High | Label containers storing black powder, one may only handle the black powder if he/she possesses a low-explosives user permit. | Have check in/out form to confirm only those permitted to handle materials are the only ones handling the material. | 5, Low |
| Workplace Fire | 2 (Unplanned ignition of flammable substance, overheated workplace, improper use or supervision of heating elements, or | 5 (Severe burns, loss of workspace, irreversible damage to project) | 10, Medium | Have fire suppression systems nearby, prohibit open flames, and store energetic devices in Type 4 magazines as stated in CFR 27 part 55. | Make sure all members are updated on the workplace fire safety protocols. Have lists of all required fire suppression system accounted for and found near the area | 5, Low |

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| | improper wiring) | | | | of work. | |

## 5.3. Failure Modes and Effects Analysis (FMEA)

| Hazard | Likelihood (Cause) | Severity (Effect) | Risk | Mitigation | Verification | Post Mitigation Risk |
|---|---|---|---|---|---|---|
| Airframe Failure | 1 (Buckling or shearing on the airframe from poor construction or use of improper materials, faulty stress modeling) | 5 (Partial or total destruction of vehicle, ballistic trajectory) | 5, Low | Use appropriate materials according to extensive mathematical and physical analyses of the body tube, bulkheads, fasteners and shear pins, make use of reliable building techniques, confirm analyses with test launches. | Use a construction checklist which ensures mathematical analyses match physical analyses, if the airframe does not perform well in test launches perform another test launch with a new airframe design before converting to full-scale, and use the launch checklists to ensure both before and after launch that the airframe is in good condition. | 5, Low |
| Failure To Launch | 2 (Lack of continuity) | 1 (Recycle launch pad) | 2, Minimal | Check for continuity prior to attempted launch. | Include checking for continuity in launch checklist that is to be completed prior to launch. | 1, Minimal |
| CATO | 1 (Motor defect, assembly error) | 5 (Partial or total destruction of vehicle) | 5, Low | Inspect motor prior to assembly and closely follow assembly instructions. | Include motor inspection in pre launch checklist to verify this task is completed. | 5, Low |
| Instability | 1 (Stability margin of less than 1.00) | 5 (Potentially dangerous flight path and loss of vehicle) | 5, Low | Measure physical center of gravity and compare to calculated center of pressure. | Have measured physical center of gravity documented and compared prior to arriving at the launch site. | 5, Low |

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| Motor Expulsion | 2 (Improper retention methods) | 5 (Risk of recovery failure and low apogee) | 10, Medium | Use positive retention method to secure motor. | Include motor securement into pre launch checklist to verify that this task is complete. | 5, Low |
| Premature Ejection | 2 (Altimeter programming, poor venting) | 5 (Zippering) | 10, Medium | Check altimeter settings prior to flight and use appropriate vent holes. Test altimeter in similar conditions to those to be experienced at launch. | Include checking altimeter settings to pre launch checklist to verify that this task is complete. Altimeter testing before launch. | 5, Low |
| Loss of Fins or Damage | 2 (Poor construction or improper materials used) | 5 (Partial or total destruction of vehicle) | 10, Medium | Use appropriate materials and high powered building techniques. | Conduct stress tests on fins to make sure they can withstand all forces present during flight. | 5, Low |
| Loss of Nose Cone | 2 (Poor construction or improper materials used) | 5 (Partial or total destruction of vehicle) | 10, Medium | Use appropriate materials and high powered building techniques. | Ensure that nose cone is secured well before ejection during test runs, otherwise alter. | 5, Low |
| Loss of Parachute | 3 (Poor construction or improper materials used) | 5 (Partial or total destruction of vehicle) | 15, High | Use appropriate materials and high powered building techniques. | Ensure that parachute is secured well before ejection during test runs, otherwise alter to lower speed. | 5, Low |
| Ejection Charge Failure | 3 (Not enough power, electrical failure) | 5 (Ballistic trajectory, destruction of vehicle) | 15, High | Ground test charge sizes at least once before flight. | Conduct voltage test readings on power source before launch to make sure appropriate power is present for launch. | 5, Low |
| Altimeter Failure | 3 (Loss of connection or improper programming) | 5 (Ballistic trajectory, destruction of vehicle) | 15, High | Secure all components to their mounts and check settings. | Include checking component securements to pre launch checklist to verify that this task is complete. | 5, Low |
| Payload Failure | 3 (Electrical failure, program | 4 (Disqualified, objectives | 12, Medium | Test payload prior to flight, check batteries and connections. | Keep fresh batteries separate from previously used | 4, Low |

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| | errors, dead battery) | not met) | | | batteries. Use fresh batteries for each launch. | |
| Heat Damaged Recovery System | 2 (Insufficient protection from ejection charge) | 5 (Excessive landing velocity, potentially ballistic trajectory) | 10, Medium | Use appropriate protection methods, such as Kevlar blankets. | Check that proper protection methods are securely placed before launch. | 5, Low |
| Broken Fastener | 1 (Excessive force) | 5 (Ballistic trajectory) | 5, Low | Use fasteners with a breaking strength safety factor of 2. | Conduct stress tests on fasteners to confirm that they meet force requirements. | 5, Low |
| Joint Failure | 2 (Excessive force, poor construction) | 5 (Partial or total destruction of vehicle, ballistic trajectory) | 10, Medium | Use appropriate joint design according to extensive mathematical and physical flight analyses, make use of reliable building techniques, confirm analyses with test launches. | Ensure by design and testing that secure. | 5, Low |
| Centering Ring Failure | 2 (Excessive force from motor, poor construction) | 5 (Partial or total destruction of vehicle, ballistic trajectory) | 10, Medium | Use appropriate centering rings according to extensive mathematical and physical flight analyses, make use of reliable building techniques, confirm analyses with test launches. | Ensure by design and testing that secure. | 5, Low |
| Battery Overcharge | 3 (Unsupervised /undocumented charge) | 3 (Destruction of battery) | 9, Medium | Ensure batteries are documented and supervised if charging. | Ensure alarms set and other individuals are aware batteries charging. | 3, Low |
| Premature Blackpowder Ignition | 2 (Accidental exposure to flame or sufficient electric charge) | 5 (Partial or complete destruction of vehicle | 10, Medium | Ensure design has sufficient distance / protection from outside, and motor, charges, and batteries. | Ensure by design and testing that secure from other systems or puncture. | 5, Low |
| Charge | 3 (Poor design | 5 (Partial or | 15, | Ensure design has | Independently | 5, Low |

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| ignition close to motor | location leads to damage) | complete destruction of vehicle | High | sufficient distance / protection from motor, charges, and batteries. | ensure design is safe; ensure by isolated testing charge may work. | |
| Destruction of Bulkheads | 2 (Poor construction or improper bulkheads chosen which cannot withstand launch forces, faulty stress modeling) | 5 (Partial or total destruction of vehicle, ballistic trajectory) | 10, Medium | Use appropriate materials according to extensive high-stress mathematical and physical analyses, make use of reliable building techniques, run stability tests, confirm analyses with test launches. | Bulkheads will be visually inspected with flashlight when possible prior to launch. | 5, Low |
| Damaged Nose Cone | 2 (Poor construction, damage from previous flights, poor storage, or transportation) | 3 (Lower launch vehicle stability, possible deviations from flight path) | 6, Low | Check the nose cone for damage before and after each launch, choose a nose cone which is strong enough to withstand launch forces according to mathematical and physical flight simulations, confirm choice of nose cone with subscale launches. | Nose cones will be inspected and repaired before and after each launch in order to make sure they are up to launch standards. | 3, Low |
| Motor Tube Angled Incorrectly | 2 (Poor construction, damage from previous flights, poor storage, or transportation) | 4 (Lower launch vehicle stability, launch vehicle does not follow desired flight path well) | 8, Medium | Ensure proper measurements and alignments are made during construction, ensure there is no rush to attach the motor tube, double-check the alignment of the motor before each flight, test that the desired motor alignment is correct with subscale flights. | Measurements will be made at 4 rotational points around the motor tube to insure equal distance from edge to launch vehicle edge coupling. | 4, Low |
| Motor Tube Comes Loose | 2 (Poor construction, damage from previous flights, poor storage, or transportation, faulty motor preparation) | 5 (Ballistic trajectory, catastrophic destruction of vehicle) | 10, Medium | Check the motor and motor tube for damage before each launch, run mathematical and physical flight simulations to ensure the tube performs as planned, confirm simulations with subscale launches. | Stress test the motor tube connection to make sure it can withstand expected forces acting upon it. | 5, Low |

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| Premature Stage Separation | 3 (Premature ejection, poor choice of shear pins or fasteners) | 5 (Possible recovery failure and damage to or loss of vehicle, ballistic trajectory) | 15, High | Check altimeter settings prior to flight, use appropriate vent holes, and run thorough analyses to determine which types of shear pins and fasteners should be used. | Redundant altimeters will be used, calibration will be checked and verified by separate individuals. | 5, Low |
| Forgotten or Lost Components | 3 (Carelessness with launch vehicle components, failure to take note of inventory before attempting to launch) | 4 (launch vehicle does not launch at the desired launch time) | 12, Medium | Have spares for components which are small and easy to lose, have an inventory of all launch vehicle parts to be checked before moving the launch vehicle to a launch site. | Make sure not to forget anything. Have a team of 2 members go through and double check that everything has been taken and is accounted for. | 4, Low |
| launch vehicle Disconnects from the Launch Rail | 2 (High wind speeds, failure to properly use the rail buttons, faulty rail buttons) | 5 (Partial or total destruction of vehicle, ballistic trajectory which endangers personnel, onlookers, and property on the ground) | 10, Medium | Use mathematical and physical analyses to ensure the rail buttons are properly aligned and working as planned, double check the rail buttons are properly attaching the launch vehicle to the launch pad before launch, test rail buttons with subscale flights. | Rail buttons will be inspected by two separate individuals prior to launch for cracks, misalignment, or other inaccuracies. | 5, Low |
| Flightpath Interference | 2 (Wildlife in the air, unforeseen obstacles such as a loose balloon) | 5 (Minor to severe change in the vehicle's flightpath, possible ballistic trajectory) | 10, Medium | Ensure there are clear skies above before launching, ensure an FAA waiver has been obtained for the designated launch area. | Visual inspection of the surrounding area to make sure no incoming wildlife or loose objects. | 5, Low |
| Unplanned Amounts of Friction Between launch vehicle and Launch Rail | 3 (Faulty setup of launch rail, faulty installation of launch vehicle on launch rail, failure to properly | 2 (launch vehicle does not follow the designated flight path well, lower maximum height) | 6, Low | Set up the rail using instructions which come with the product, use lubrication on the rail as needed according to weather and rail type, ensure the launch vehicle is | Launch rails will be tested by tactile inspection to insure proper lubrication. | 2, Minimal |

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| | lubricate launch rail as needed, weather conditions cause excess friction) | | | properly installed on the launch rail. | | |
| Failure to Ignite Propellant | 2 (Faulty motor preparation, poor quality of propellant, faulty igniter, faulty igniter power source, damage to motor) | 5 (launch vehicle does not immediately launch and is a considerable hazard until it is confirmed that it will not launch, changes to igniters or launch vehicle required) | 10, Medium | Purchase propellant and motors only from reliable sources, team members who prepare the motor and igniters must be supervised by at least one other team member, determine if the igniters chosen work well during subscale testing. | Make sure igniters are well tested and are extremely reliable. | 5, Low |
| Propellant Fails to Burn for Desired Duration | 2 (Faulty motor preparation, poor quality of propellant, damage to motor) | 3 (launch vehicle does not follow the designated flight path well, lower maximum height, if drastic change in maximum height the ejection charges for recovery may not deploy) | 6, Low | Purchase propellant and motors only from reliable sources, check the motor for damage prior to launching, team members who prepare the motor must be supervised by at least one other team member. | Team member will be designated to observe the motor preparation procedure, only approved propellant sources will be used. | 3, Low |
| Propellant Burns Through launch vehicle Components | 2 (Faulty motor preparation, poor quality of propellant, poor construction, damage to motor, damage to propellant | 5 (Ballistic trajectory, catastrophic destruction of vehicle) | 10, Medium | Purchase propellant and motors only from reliable sources, check the motor for damage prior to launching, team members who prepare the motor must be supervised by at least one other team member, test propellant casing in | Double check bulkhead after every flight to make sure it is in good enough condition for it to sufficiently protect launch vehicle components from propellent exhaust. | 5, Low |

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| | casing) | | | subscale flights. | | |
| Propellant Explosion | 1 (Faulty motor preparation, poor quality of propellant, damage to motor) | 5 (Ballistic trajectory, catastrophic destruction of vehicle, possible harm to bystanders) | 5, Low | Purchase propellant and motors only from reliable sources, check the motor for damage prior to launching, team members who prepare the motor must be supervised by at least one other team member. | Team member will be designated to observe the motor preparation procedure, only approved propellant sources will be used. | 5, Low |
| Payload Computer Failure | 3 (Electrical failure, program error, poor setup of wiring causes a connection to come undone, forgotten connection, battery failure) | 5 (Disqualified, objectives not met, loss of electronic control) | 15, High | Test payload prior to flight, check batteries and connections before flight. | Ensure by design and testing that components will not fail under extreme stress. | 5, Low |
| Power Loss to Avionics Bay and/or Payload | 3 (Faulty wiring, battery failure, poor setup of wiring causes a connection to come undone, forgotten connection) | 5 (Disqualified, objectives not met, failure to correctly trigger ejection charges) | 15, High | Test the reliability of the wiring and batteries through subscale flights, check batteries and connections before flight. | Continuity checks will be used, visible wires will be inspected for nicks or damage prior to launch. | 5, Low |
| Avionics Bay Fire | 2 (Faulty wiring, battery failure, poor setup of wiring, adverse weather) | 5 (May be disqualified if objectives are not met, possible failure to trigger ejection charges, damage to internal launch vehicle components) | 10, Medium | Thermal protection of avionics bay, do not overload avionics bay with wiring, only purchase avionics and payload equipment from reliable sources, check avionics bay and payload performance with test launches. | Make sure no wires are exposed and that the avionics bay is sufficiently protected from heat. | 5, Low |
| Human Error When | 3 (Forgotten connection, | 5 (Disqualified, | 15, High | Leave reminders in multiple places to | All designated launch procedure | 5, Low |

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| Arming Avionics and Payload | forgetting to activate avionics bay components or payload prior to launch) | objectives not met, failure to correctly trigger ejection charges) | | check that the avionics bay and payload are armed and ready before launch, follow launch checklists closely. | observers will inspect avionics for charge and activation. | |
| Arming System Failure | 3 (Faulty arming system, faulty wiring, battery failure, poor setup of wiring causes a connection to come undone, forgotten connection) | 5 (Disqualified, objectives not met, failure to correctly trigger ejection charges) | 15, High | Ensure the avionics bay is successfully communicating with the team prior to flight, test arming system through test launches. | Ensure by design and testing that communication between components is established and reliable. | 5, Low |
| Poor Spacing Between the Ejection Charge and the Parachute | 2 (Failure to properly consider the requirements of the recovery system, poor budgeting of space in launch vehicle, failure to read instructions that come with parachute and/or ejection charges) | 5 (Partial or total damage to the parachute, parachute does not launch from the launch vehicle, possible recovery failure) | 10, Medium | Read all instructions which come with the parachute and ejection charges, establish clear requirements of the recovery system early in the design process, run mathematical and physical analyses on the design of the launch vehicle, ensure the parachute is spaced properly with subscale test flights. | Dual analysis will be performed to insure no damage occurs to the parachute, ejection charge testing to insure no parachute damage. | 5, Low |
| Stage Fails to Separate | 3 (Faulty ejection charge, excessive strength is used to hold stages together, altimeter failure) | 5 (launch vehicle does not follow desired flight path, possible ballistic trajectory, lower maximum height, damage to the launch vehicle) | 15, High | Any team member who loads the ejection charges must be supervised by at least one other team member, examine ejection charges for damage before launch, ensure proper functionality of the altimeters, ejection charges, and interstage joints and fasteners through test flights and mathematical and | Ejection charge testing will be performed to insure charges can separate stages, dual altimeters will be employed to enable redundancy. | 5, Low |

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| | | | | physical analyses, have a secondary ejection charge for each stage separation. | | |
| Main Parachute Fails to Deploy | 2 (Poor design of where parachute is in launch vehicle, poor sealing of parachute chamber, poor loading of parachute, faulty parachute or ejection charge, altimeter failure) | 5 (Main parachute does not slow down the launch vehicle, recovery failure, ballistic trajectory) | 10, Medium | Any team member who seals or packs the parachute chamber must be supervised by at least one other team member, examine parachute and ejection charges for damage before launch, run mathematical and physical analyses as well as subscale tests to ensure parachute is in the right position in the launch vehicle, have a secondary ejection charge in case of emergency which is larger than the first. | Ejection charge testing will be done to insure charge effectively deploys parachute. | 5, Low |
| Drogue Parachute Fails to Deploy | 2 (Poor design of where parachute is in launch vehicle, poor sealing of parachute chamber, poor loading of parachute, faulty parachute or ejection charge, altimeter failure) | 5 (Drogue parachute does not slow down the launch vehicle, recovery failure, ballistic trajectory) | 10, Medium | Any team member who seals or packs the parachute chamber must be supervised by at least one other team member, examine parachute and ejection charges for damage before launch, run mathematical and physical analyses as well as subscale tests to ensure parachute is in the right position in the launch vehicle, have a secondary ejection charge in case of emergency which is larger than the first. | Double check that packing of the drogue parachute to ensure that it reliably deploys. | 5. Low |
| Parachute Canopy Breaks or Tears | 1 (Poor canopy materials, improper ejection of recovery system, damage from | 5 (Possible recovery failure, ballistic trajectory) | 5, Low | Only buy parachutes from reliable sources, remove threats to parachute integrity from the parachute housing, test the recovery system through mathematical | Run simulations and mathematical analysis to ensure the acquired parachute is capable of withstanding forces to safely descend | 5, Low |

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| | previous flights or transportation) | | | and physical analyses as well as subscale flights, check the recovery system for damage before launch. | the launch vehicle. | |
| Parachute Shroud Lines Break | 1 (Poor shroud line materials, improper ejection of recovery system, damage from previous flights or transportation) | 5 (Possible recovery failure, ballistic trajectory) | 5, Low | Only buy parachutes from reliable sources, remove threats to parachute integrity from the parachute housing, test the recovery system through mathematical and physical analyses as well as subscale flights, check the recovery system for damage before launch. | Ensure by design and testing that the shroud lines are strong enough to handle expected forces. | 5, Low |
| Shock Cord Break or Disconnect | 1 (Faulty shock cord, damage to shock cord, poor connection to the launch vehicle) | 5 (Parachute disconnect from the launch vehicle, recovery failure, ballistic trajectory) | 5, Low | Any team member who connects the shock cord to the launch vehicle must be supervised by at least one other team member, check the shock cord for damage before and after flight, only buy shock cords from reliable sources, analyze the shock cord with test flights. | Test the shock cord to ensure it can withstand the forces acting upon it during descent. | 5, Low |
| Tangled Parachute or Shock Cord | 2 (Faulty or damaged shock cord or parachute, poor packing of shock cord and/or parachutes, poor sizing of parachutes or shock cord, unstable or ballistic flight) | 5 (Shock cord or parachutes may not fully achieve their goal, possible ballistic trajectory, possible failed recovery) | 10, Medium | Only buy parachutes and shock cords from reliable sources, any team member who seals or packs the parachute chamber must be supervised by at least one other team member, examine parachutes and shock cord for damage before launch, check performance of parachutes and shock cord in test flights, appropriately follow recommended sizings for shock cord and parachutes. | Designated parachute packing observer will record the packing and make notes on operation, and have right to demand repacking. | 5, Low |

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| Parachute Comes Loose from launch vehicle | 2 (Failure of recovery system mount on the launch vehicle body, poor shroud line materials, improper ejection of recovery system, damage from previous flights or transportation) | 5 (Recovery failure, ballistic trajectory) | 10, Medium | Only buy parachutes from reliable sources, test the recovery system through mathematical and physical analyses as well as subscale flights, check the recovery system for damage before launch, double check that the recovery system is properly mounted before launch. | Ensure by design and testing that the parachute is attached well. | 5, Low |
| Parachute or Shock Cord Catch Fire | 2 (Not enough space given between ejection charge and parachute, poor insulation of parachute, poor parachute packing, faulty or poorly chosen ejection charge) | 5 (Shock cord or parachutes do not fully achieve their goal, possible ballistic trajectory, possible failed recovery, damage to internal launch vehicle components) | 10, Medium | Any team member who packs the parachute or ejection charges must be supervised by at least one other team member, use recommended sizing methods for ejection charges, confirm proper placement and packing methods of ejection charges and parachutes with test flights. | Designated packing operation observer will document packing process to insure proper placement. | 5, Low |
| Destruction Due To Drag Forces | 1 (Poor construction or improper materials used) | 5 (Partial or total destruction of vehicle) | 5, Low | Use appropriate materials and high powered building techniques. | Test subscale in wind tunnel and use dynamic similarity of coefficient of drag to estimate drag on full scale. | 5, Low |
| Airframe Zipper | 2 (Excessive deployment velocity) | 5 (Partial destruction of vehicle) | 10, Medium | Properly time ejection charges and use an appropriately long tether. | Test and observe at full scale launch prior to Huntsville. | 5, Low |
| GPS Lock Failure | 2 (Interference or dead battery) | 5 (Loss of vehicle) | 10, Medium | Ensure proper GPS lock and battery charge before flight. | Check battery charge before flight to ensure it is capable of providing power during the duration of flight. | 5, Low |
| Insufficient | 3 (Improper | 2 | 6, Low | Use subscale flights to | Dual simulations | 2, Minimal |

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| Landing Speed | load, higher coefficient of drag for the parachutes than needed, higher surface area of the parachutes than needed) | (Unexpected changes in flightpath and landing area, increased potential for drift) | | determine if the subscale parachutes were accurately sized, use recommended and proven-to-work parachute sizing techniques. | will validate theoretical parachute performance. | |
| Excessive Landing Speed | 3 (Parachute damage or entanglement, improper load) | 5 (Partial or total destruction of vehicle) | 15, High | Properly size, pack, and protect parachute. | Test and observe at full scale launch prior to Huntsville. | 5, Low |
| Battery Leakage/ Combustion | 2 (Battery compartment becomes punctured) | 5 (Potential for ballistic trajectory) | 10, Medium | Check battery integrity before each launch. | Include checking battery condition in pre launch checklist. | 5, Low |

## 5.4. Environmental Hazard Analysis

| Hazard | Likelihood (Cause) | Severity (Effect) | Risk | Mitigation | Verification | Post Mitigation Risk |
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| Landscape | 3 (Trees, brush, water, power lines, wildlife) | 5 (Inability to recover launch vehicle) | 15, High | Angle launch vehicle into wind as necessary to reduce drift. | Inspect launch site before launch to verify that it is a suitable area to launch. | 5, Low |
| Humidity | 3 (Climate, poor forecast) | 1 (Rust on metallic components) | 3, Low | Use as little metal as possible, store indoors. | Check weather beforehand for ideal launch time. | 1, Minimal |
| Winds | 3 (Poor forecast) | 4 (Inability to launch, excessive drift) | 12, Medium | Angle into wind as necessary and abort if wind exceeds 20 mph. | Check weather beforehand for ideal launch time. | 4, Low |
| High Temperature | 3 (Poor forecast) | 3 (Heat related injury or damage) | 9, Medium | Keep launch vehicle in shaded area until before launch. | Check weather beforehand for ideal launch time. | 3, Low |
| Low Temperatures | 3 (Poor forecast) | 3 (Cold-related personnel injuries, Frost on ground, ice on vehicle, | 9, Medium | Ensure team is wearing appropriate clothing for extended periods of time in cold environments, | Ensure team is notified of all weather on day of launch or manufacturing to | 3, Low |

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| | | clogging of vehicle ventilation, change in launch vehicle rigidity and mass, higher drag force on launch vehicle) | | keep the launch vehicle at room temperature or bundled in materials which hold in heat, if ice appears anywhere on the launch vehicle do not launch and return it to a warm location. | wear proper clothing; do not launch if weather below designed intent of launch vehicle; ensure mitigation is strictly followed due to weather notification. | |
| Pollution From Exhaust | 5 (Combustion of APCP motors) | 1 (Small amounts of greenhouse gasses emitted) | 5, Low | Use only launch vehicle motors approved for use by the National Association of launch vehiclery, Canadian Association of launch vehiclery, or Tripoli RocketryAssociation. | launch vehicle motors in consideration will be checked by a safety team member to ensure compliance. | 5, Low |
| Pollution From vehicle | 2 (Loss of components from vehicle) | 3 (Materials degrade extremely slowly, possible harm to wildlife or water contamination) | 6, Medium | Properly fasten all components. Scavenge for fallen parts after launch is completed. | Inspect the securements of components before launch. Have designated clean up team for each launch. | 3, Low |
| Pollution from Team Members | 2 (Failed disposal of litter, improper cleanup procedures, members walk through important plantlife, farming fields, sod, etc.) | 4 (Litter may degrade extremely slowly, wildlife may consume harmful litter) | 8, Medium | Brief team members on proper cleanup procedures, foster a mindset of leaving no trace at launch sites, only the minimum number of required team members should retrieve the launch vehicle. | Follow societal standards and leave cite cleaner than was found; make sure disposable equipment is kept track of and guaranteed to remain at designated locations, not with retrieval. | 4, Low |
| Collisions with Man-made Structures or with Humans | 2 (Failure to properly predict trajectory, failure to choose an appropriate launch area) | 5 (Damage to public property or private property not owned by the team, damage to team equipment, serious damage | 10, Medium | Do not launch under adverse conditions which may affect the course of the launch vehicle, run a large number of tests which analyze the launch vehicle's trajectory | Run tests to analyze and estimate the launch vehicle's trajectory so that the launch vehicle's path is known to the team; do not launch launch vehicle under adverse weather | 5, Low |

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| | | to team personnel or passerby) | | mathematically and physically, choose a launch area which is not close to civilization, follow launch procedures closely. | conditions and choose a launch location which allows for open space to avoid accidents. | |
| Wildlife Contact with launch vehicle | 1 (Failure to accurately predict trajectory, unexpected appearance of wildlife, poor choice of launch area) | 4 (Damage to vehicle components, damage to wildlife, unexpected trajectory close to the ground) | 4, Low | Launch in an open area with high visibility, be aware of the surroundings when choosing a launch area and launching. | Ensure that the launch area is in a safe area where surroundings don't stand in the way of the launch or have a chance of getting damaged. | 4, Low |
| Wildlife Contact with Launch Pad | 1 (Failure to monitor the launch pad, poor choice of launch area) | 4 (Possible inability to launch the launch vehicle, unpredictable launch behavior or trajectory) | 4, Low | Have at least one team member monitoring the launch pad at all times, launch in an open area with high visibility, be aware of the surroundings when choosing a launch area and launching, if animals tamper with the launchpad do not launch. | Ensure that the launch pad is in a safe area where surroundings don't stand in the way of the launch pad or have a chance of getting damaged by the launch. | 4, Low |
| Battery Leakage | 3 (Absence of or damage to battery casing causing puncture) | 3 (Possible toxic acid leak, heavy metal contamination) | 9, Medium | Batteries will be individually enclosed in plastic casing, parachutes will be selected to reduce landing kinetic energy below levels that will damage the casing. | Inspect battery casing prior to launch to ensure the battery is properly protected and unlikely to become punctured. | 6, Low |
| Fire to Surroundings | 5 (Exhaust caused by launch vehicle engine) | 5 (Possible spread of wildfire) | 25, Very High | Ground will be cleared per NAR standard, fire extinguishers will be on hand, flame retardant tarp will be deployed to prevent catching of fire. | Inspection by safety officer will be performed to ensure compliance with NAR safety standard on minimum clear area. | 5, Low |

| | | | | | | |
|---|---|---|---|---|---|---|
| Kinetic Damage to Buildings | 2 (launch vehicle veers off trajectory causing landing in occupied area) | 4 (Repairable destruction to building) | 8, Medium | Choose launch site that is remote enough to make this risk negligible. | Ensure minimum distance from building exceeds minimum personnel distance as established by NAR safety standard. | 4, Low |
| Kinetic Damage to Terrain | 4 (launch vehicle has excessive landing speed) | 1 (Creation of small ground divets, mild inconvenience to wildlife and flora) | 4, Low | Simulate landing conditions to ensure parachute generates sufficient drag to slow launch vehicle to acceptable parameters | Dual simulations will be performed to ensure proper parachute performance. | 2, Minimal |

## 5.5. Project Risks Analysis

| Hazard | Likelihood (Cause) | Severity (Effect) | Risk | Mitigation | Verification | Post Mitigation Risk |
|---|---|---|---|---|---|---|
| Improper Funding | 3 (Lack of revenue) | 5 (Inability to purchase parts) | 15, High | Create and execute a detailed funding plan properly, minimize excessive spending by having multiple members check the necessity of purchases. | Have each team verify purchases with team lead to ensure the team is still within their given budget. | 5, Low |
| Failure To Receive Parts | 2 (Shipping delays, out of stock orders) | 5 (Cannot construct and fly vehicle) | 10, Medium | Order parts while in stock well in advance of needed date. | Order parts a month before needed. Acquire lead time from supplier for accountability. | 5, Low |
| Damage to or Loss of Parts | 2 (Failure during testing, improper part care during construction, transportation , or launch) | 5 (Cannot construct or fly vehicle without spare parts) | 10, Medium | Have extra parts on hand in case parts need to be replaced, follow all safety procedures for transportation, launch, and construction. | Confirm a minimum number of parts needed so the team is able to obtain duplicates for certain parts. Assign responsibility for more important and expensive parts. | 5, Low |

| | | | | | | |
|---|---|---|---|---|---|---|
| Rushed Work | 2 (Rapidly approaching deadlines, unreasonable schedule expectations) | 4 (Threats of failure during testing or the final launch due to a lower quality of construction and less attention paid to test data) | 8, Medium | Set deadlines which both keep the project moving at a reasonable pace and leave room for unforeseen circumstances. | Have team leads verify that projects are being completed before the deadline arrives. | 4, Low |
| Major Testing Failure | 2 (Improper construction of the launch vehicle, insufficient data used before creating the launch vehicle's design) | 5 (Damage to vehicle parts, possible disqualification from the project due to a lack of subscale flight data, an increase in budget for buying new materials, delay in project completion) | 10, Medium | Ensure parts used fall within specifications of required use. Take care to perform tests correctly. | Conduct proper tests to ensure that the designs are in fact reliable. | 5, Low |
| Unavailable Test Launch Area | 2 (Failure to locate a proper area to launch subscale launch vehicles for testing, failure to receive an FAA waiver for the test launch) | 5 (Disqualificatio n from the project due to a lack of subscale flight data) | 10, Medium | Secure a reliable test launch area and FAA waiver well in advance of the dates on which test launch data is required. | Schedule a launch date a well in advance and set a deadline for when the FAA waiver is to be completed and submitted. | 5, Low |
| Loss or Unavailability of Work Area | 1 (Construction, building hazards, loss of lab privileges) | 4 (Temporary inability to construct vehicle) | 4, Low | Follow work area regulations and have secondary spaces available. | Inform members of proper work area etiquette to prevent loss of lab privileges. Regularly confirm that the team has access to secondary locations if the need arises. | 4, Low |
| Failure in | 1 (Improper | 3 (Possible | 3, Low | Ensure proper | Inspect | 3, Low |

| | | | | | | |
|---|---|---|---|---|---|---|
| Construction Equipment | long-term maintenance of construction equipment, improper use or storage of equipment) | long-term delay in construction) | | maintenance and use of construction equipment and have backup equipment which can be used in case of an equipment breakdown. | equipment before and after use to confirm the equipment is functioning properly. | |
| Insufficient Transportation | 1 (Insufficient funding or space available to bring all project members to launch sites or workplace) | 3 (Loss of labor force, team members lose knowledge of what is happening with the project, low attendance to the final launch) | 3, Low | Organize and budget for transportation early and keep track of dates on which large amount of transportation are needed. | Organize transportation for at least a month in advance and make sure either enough drivers are secured or buses are rented. | 3, Low |
| Inactivity / Low Availability of Personnel | 2 (Members are unable or unwilling to work due to an increase in classwork or other mandatory activities) | 5 (Low attendance, loss of team members, labor shortages, inability to construct vehicle) | 10, Medium | Train all members to work in all areas necessary. | Utilization of work time table. | 5, Low |
| Damage By Non-Team Members | 1 (Accidental damage caused by other workspace users) | 5 (Extensive repairs necessary, delay in construction) | 10, Medium | Separate all components from other areas of the workspace as necessary. | Ensure only team members as known can have access to components. | 5, Low |
| Damage During Transit | 2 (Mishandling during transportation ) | 5 (Inability to fly launch vehicle) | 10, Medium | Protect all launch vehicle components during transit. | Ensure launch vehicle safety secured by testing. | 5, Low |
| Weather Delays | 3 (Poor weather conditions during test launches, such as high wind speeds, ice and frost, or storms) | 5 (Possible disqualification from the project due to a lack of subscale flight data) | 15, High | Have multiple dates available on which test launches can be conducted in case of adverse weather conditions. | Have backup date planned before. | 5, Low |

## 5.6. Launch Checklists

In preparation for actual launch procedures, checklists have been created to maintain continuity of launch operations, to alleviate possible ambiguity in launch operation. Alleviation of such conditions is critical not only to an efficient launch operation, but also a safe launch: continuity means predictability, and predictability not only reduces the number of launch elements that can go catastrophically wrong, but also allow bystanders to recognize and prepare in the unlikely and unfortunate event that the launch does go catastrophically wrong. In addition, the creation of these checklists allows the team to create contingencies against worst case scenarios, namely misfires or unintended ballistic trajectories. While there is no way to truly abate the danger associated with the latter, preparation and the creation of a contingency is the best method for reducing the risk of tragedy.

### 5.6.1. Pre-Launch Checklist

General Safety

- ❏ Ensure that at least two people are using this checklist to prep for launch
- ❏ Ensure that a trained Range Safety Officer is present
- ❏ Have first aid equipment and at least one phone available for use nearby
- ❏ Designate a "rapid response" person or persons to be the one(s) to perform duties such as administering first aid in the case of an emergency
- ❏ Designate spotters to keep track of the launch vehicle's descent and to point out its location as it falls
- ❏ Have adequate fire suppression equipment available for use nearby
- ❏ A fire blanket has been placed under the pad if conditions at launch are dry enough to require it

General launch vehicle Construction (To be done after prepping avionics and reloads)

- ❏ Ensure computer simulations have already been run of the launch vehicle in its current construction state before launch to analyze both normal and ballistic scenarios
- ❏ Check that all fins and lugs are secure and aligned
- ❏ Check that the body tube is in good condition
- ❏ Check that the motor and ejection system are in good condition, are functional, and are securely installed
    - ❏ Ensure the proper motor and ejection have been selected for the desired flight profile and that they are certified by NAR, Tripoli, or CAR
    - ❏ Check the reload motor for proper build-up, paying special attention to the O-rings
    - ❏ Ensure the ejection charge is properly installed, and is the proper amount according to the table at the end of this checklist (Figure 2)
    - ❏ Check that the motor mount is secure, is in good condition, and will not deflect motor thrust
- ❏ Check that the recovery system is in good condition, is functional, is securely installed, and is strong enough to withstand recovery loads
    - ❏ Check that shock cords are securely attached and are not cracked, burned, or frayed
    - ❏ Check that shroud lines are not burned or tangled
    - ❏ Check that all hardware, such as snap swivels and screw eyes, is in good condition and secure
    - ❏ Check that parachute protection is installed properly and is in good condition
- ❏ Check that the electronics bay is in good condition, is functional, and is securely installed

- ❏ Have each altimeter checked the **night before** the flight
- ❏ Ensure the altimeters are properly installed
- ❏ Check that the avionics are initially disarmed and that an “Arm before flight” reminder is in use
- ❏ Check that the electronics bay is properly vented and that wires do not cover any ports
- ❏ Check that the drogue and main wiring are in good condition
- ❏ Check that all electronics bay hardware and electrical connections are secured against acceleration forces
- ❏ If appropriate, check the settings of the mach lock-out / mach delay
- ❏ Ensure the battery or batteries being used are charged and in operational condition, and secure battery positions with masking tape
- ❏ Check that the ejection charges are properly set up
- ❏ Close and secure the electronics bay

Flight Check

- ❏ Check the nose cone and any stage or payload couplers for a secure and proper fit
- ❏ Check that the motor is securely installed
- ❏ Check for continuity, resistance, and cracks or flaws in the pyrogen of the igniters; all igniters must touch the propellant, have adequate electrical current flowing to them, and have no shorts
- ❏ If clustering, ensure thrust symmetry
- ❏ Check that staging delay is less than one second
- ❏ Ensure that the center of gravity and center of pressure are in their expected positions
- ❏ Perform manufacturer’s checking instructions on the avionics
- ❏ Check that shear pins are installed for main parachute compartment
- ❏ Ensure drogue ejection will not cause main to deploy

Pad Distance

- ❏ Only the minimum number of personnel are at the pad to prep for launch
- ❏ All team personnel and spectators are a safe distance from the pad based upon a minimum distance table; use the table at the end of this checklist (Figure 1)
- ❏ Ensure barriers are in place to keep spectators away from the launch area

Pad Installation

- ❏ Ensure the launch controller is disarmed prior to installing the launch vehicle onto the pad
- ❏ Ensure the launch pad is stable and is an adequate size for the launch vehicle being used
- ❏ Ensure that enough electrical current will reach the igniters of the launch vehicle
- ❏ Verify that the igniter clips are clean and the leads are secured to the pad
- ❏ Verify that the launch vehicle moves smoothly on the launch rail; clean the rail and launch vehicle as necessary
- ❏ Ensure that the igniter clips are clean and secure them to the pad; install igniter into motor
- ❏ Connect launch leads to motor igniter
- ❏ Arm the avionics system once the launch vehicle is on the pad
    - ❏ Ensure that the Raspberry Pi systems are all turned on!

Flight Trajectory

- ❏ Ensure the launch and the flight will not be angled towards any spectators
- ❏ Double check that the launch vehicle will not fly higher than its permitted clearance waiver; know the expected performance of the model

- ❏ Check cloud bases and winds and make sure the skies around the launch area are clear
- ❏ If needed, use a wind speed indicator to avoid launching during extremely windy intervals
- ❏ Ensure there are no obstructions or hazards in the launch area

Beginning the Launch

- ❏ Shortly before the countdown, give a **loud** announcement that the launch vehicle will be launched; if applicable to the situation, use a PA system
- ❏ Ensure that all spectators are aware of the launch and that parents are in close contact with all children
- ❏ When launching, give a **loud** countdown of “5, 4, 3, 2, 1, LAUNCH!”

### 5.6.2. Launch Checklist

- ❏ Ensure that at least two people are using this checklist to observe the launch
- ❏ Ensure the stability of the model is being monitored
- ❏ Ensure that the recovery system is successfully deployed.
- ❏ Carry out a safe recovery of the model
- ❏ If radio control is used for flight functions (e.g. recovery), check that the operating frequency is in the 27, 50, 53, or 72 megahertz bands. Use of 75 megahertz for flight functions is not permitted.
- ❏ Ensure launch vehicle trajectory is being tracked during flight. Be aware of tilt or drift from mass/aerodynamic imbalance, wind, or other sources. **Do not turn off the altimeters.**
- ❏ Ensure crosswind positioning of spectators and vehicles
- ❏ Ensure that the launch pad is being monitored after takeoff in case any dangers arise at the pad
- ❏ Ensure all passerby and spectators are aware of the launch
- ❏ Call a loud “Heads up!” (If needed, sound an air horn) in the case of any launch vehicles approaching the prep area or spectators; all who see the incoming launch vehicle should point at it as it descends.
- ❏ Monitor the flight path, using binoculars if necessary
- ❏ Make sure whoever is responsible for recovery is kept fully aware of the status of the launch vehicle (failed to launch, nominal in-flight, mid air failure, returning for recovery, etc.)
- ❏ Communicate launch progress effectively to NASA officials, if needed

In the case of a misfire:

- ❏ Wait a minimum of one minute
- ❏ Disarm launch controller and avionics
- ❏ Remove failed igniter and motor if needed

In the case of unintended ballistic trajectory

- ❏ Should the launch vehicle fall below a predetermined altitude (around 700 feet, but precise number to be determined later) without any indication of parachute ejection (smoke from ejection charge, parachute deploying), those tasked with observing the trajectory will loudly announce “Scatter”.
- ❏ All in attendance of the launch are to immediately turn away from the direction of the launch vehicle and run for a minimum of 7 seconds

Note: when launching through an affiliate launch day, team emergency contingencies are superseded by launch day procedures.

#### 5.6.3. Post-Launch Checklist

- ❑ Ensure that at least two people are using this checklist after launch
- ❑ Double check that there are no hazards which have gone unnoticed during the launch before approaching the launch pad or the launch vehicle for clean-up.
  - ❑ If there are hazards, notify emergency personnel
- ❑ Let NASA officials verify the results of the launch, if necessary
- ❑ Double check that all necessary data from the avionics bay has been retrieved
  - ❑ If so, disarm the avionics
- ❑ Disarm the launch controller
- ❑ Place cap on launch rods, if necessary
- ❑ Take down the launch pad, if necessary
- ❑ Retrieve the main launch vehicle body and all components which may have landed separately
  - ❑ Check them for any failed ejection charges
  - ❑ If there are failed ejection charges, safe all ejection circuits and remove any non-discharged pyrotechnics

# 6. Project Plan

Topics discussed in this section will include derived requirements by NASA and PSP-SL's plan to verify that the team will meet and/or exceed these requirements, derived requirements by the PSP-SL Executive board and how the team will meet and exceed these requirements, a timeline for the competition, a line by line budget for the team, funding plan, and a section discussing PSP-SL's STEM educational outreach.

## 6.1. NASA Derived R&VP

The following list of requirements are derived by the NASA Student Launch team and need to be completed and followed in order to ensure that the PSP-SL team is constantly meeting the safety standards of high powered flight and completing the goals set by the Student Launch team. The PSP-SL team has looked at all requirements and broken each into several sections to ensure that the team is meeting / exceeding each NASA derived requirement. The sections are as follows: General Requirements & Verification Plans (R&VP), Vehicle R&VP, Avionics & Recovery R&VP, Payload R&VP, and Safety R&VP. Each of the above sections will be broken into individual requirements and will be verified via one of 4 ways: Inspection, Demonstration, Test, and / or Analysis.

1. **Inspection:** thorough examination of the system or process using physical manipulation, measurements, or observation via the five human senses.
2. **Demonstration:** manipulation of a given system or process intended to verify that the results match the expected results.
3. **Test:** verification of a given system or process through the use of a procedure, given relevant inputs, to ensure that the system or process meets and exceeds expected results specified in the requirements.
4. **Analysis:** verification of a given system or process through utilizing calculations, academic theory, and system models.

Each of the following requirements, both team derived and NASA derived, has been given a unique ID number which references the requirements from the NASA Student Launch Handbook, written by the NASA Student Launch team.

Additionally, the PSP-SL team has generated a table format which organizes R&VP for each requirement. Each table lists requirement ID, the requirement's description, the team's verification plan for the requirement, additional comments for the requirement (if applicable), the ID for the test which verifies the requirement (if applicable), the status of the requirement (complete or incomplete), and one of four colors which indicates the type of verification. These colors are shown along the left side of each table, and multiple colors means multiple methods of verification. For requirements which are not applicable to the PSP-SL team, these colors were left as white, as was the coloration of the verification status box. A guide to which color corresponds to each verification method follows:

| | |
|---|---|
| **Inspection** | **Demonstration** |
| **Analysis** | **Test** |

### 6.1.1. General R&VP

| | |
|---|---|
| **Requirement ID:** 1.1<br>**Description:**<br>Students on the team will do 100% of the project, including design, construction, written reports, presentations, and flight preparation with the exception of assembling the motors and handling black powder or any variant of ejection charges, or preparing and installing electric matches (to be done by the team's mentor). Teams will submit new work. Excessive use of past work will merit penalties. | **Verification Plan:** PSP-SL members will demonstrate the new work they have completed by submitting milestone documents and will demonstrate the understanding they have gained by doing the work themselves during PowerPoint presentations. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

| | |
|---|---|
| **Requirement ID:** 1.2<br>**Description:**<br>The team will provide and maintain a project plan to include, but not limited to the following items: project milestones, budget and community support, checklists, personnel assignments, STEM engagement events, and risks and mitigations. | **Verification Plan:** Project plan completion will be demonstrated by turning in the milestone reports which contain it. |
| | **Comments:** N/A |
| **Status:** Complete | **Verification Test ID:** N/A |

| | |
|---|---|
| **Requirement ID:** 1.3<br>**Description:**<br>Foreign National (FN) team members must be identified by the Preliminary Design Review (PDR) and may or may not have access to certain activities during launch week due to security restrictions. In addition, FN's may be separated from their team during certain activities on site at Marshall Space Flight Center. | **Verification Plan:** Foreign national team members' contact information will be demonstrated when it is submitted alongside PDR documentation. |
| | **Comments:** N/A |
| **Status:** Complete | **Verification Test ID:** N/A |

| | |
|---|---|
| **Requirement ID:** 1.4<br>**Description:**<br>The team must identify all team members attending launch week activities by the Critical Design Review (CDR). Team members will include:<br>• Students actively engaged in the project throughout the entire year.<br>• One mentor (see requirement 1.13).<br>• No more than two adult educators. | **Verification Plan:** PSP-SL member contact information will be demonstrated when it is submitted alongside CDR documentation. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

| Requirement | Verification |
|---|---|
| **Requirement ID:** 1.5<br>**Description:**<br>The team will engage a minimum of 200 participants in educational, hands-on science, technology, engineering, and mathematics (STEM) activities, as defined in the STEM Engagement Activity Report, by FRR. To satisfy this requirement, all events must occur between project acceptance and the FRR due date and the STEM Engagement Activity Report must be submitted via email within two weeks of the completion of the event. | **Verification Plan:** STEM Engagement Activity Reports will be completed and demonstrated to the NASA Student Launch team via email throughout the course of the project. Activity Reports will be submitted within a week of each event occurring so documentation can be written accurately.<br>**Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

| Requirement | Verification |
|---|---|
| **Requirement ID:** 1.6<br>**Description:**<br>The team will establish a social media presence to inform the public about team activities. | **Verification Plan:** PSP-SL's social media information will be publicly available online and links to each social media outlet of the team will be provided to the NASA Student Launch team.<br>**Comments:** N/A |
| **Status:** Complete | **Verification Test ID:** N/A |

| Requirement | Verification |
|---|---|
| **Requirement ID:** 1.7<br>**Description:**<br>Teams will email all deliverables to the NASA project management team by the deadline specified in the handbook for each milestone. In the event that a deliverable is too large to attach to an email, inclusion of a link to download the file will be sufficient. | **Verification Plan:** All deliverables will be demonstrated to the NASA project management via email by the deadlines listed in the Project Plan section. All milestone deliverables will be completed at least a week in advance so they can be reviewed and submitted on time.<br>**Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

| Requirement | Verification |
|---|---|
| **Requirement ID:** 1.8<br>**Description:**<br>All deliverables must be in PDF format. | **Verification Plan:** The altitude will be determined through simulation with open launch vehicle.<br>**Comments:** N/A |
| **Status:** Complete | **Verification Test ID:** N/A |

| | |
|---|---|
| **Requirement ID:** 1.9<br>**Description:**<br>In every report, teams will provide a table of contents including major sections and their respective sub-sections. | **Verification Plan:** Tables of contents will be included at the beginning of each milestone report and will be included when the report is submitted to the NASA Student Launch Team. |
| | **Comments:** N/A |
| **Status:** Complete | **Verification Test ID:** N/A |

| | |
|---|---|
| **Requirement ID:** 1.10<br>**Description:**<br>In every report, the team will include the page number at the bottom of the page. | **Verification Plan:** Each milestone report submitted to the NASA Student Launch team will have a page number visible at the bottom-right corner of each page. |
| | **Comments:** N/A |
| **Status:** Complete | **Verification Test ID:** N/A |

| | |
|---|---|
| **Requirement ID:** 1.11<br>**Description:**<br>The team will provide any computer equipment necessary to perform a video teleconference with the review panel. This includes, but is not limited to, a computer system, video camera, speaker telephone, and a sufficient Internet connection. Cellular phones should be used for speakerphone capability only as a last resort. | **Verification Plan:** PSP-SL will demonstrate its capability to conduct video teleconferences by participating in all milestone presentation conferences with the NASA Student Launch team. |
| | **Comments:** N/A |
| **Status:** Complete | **Verification Test ID:** N/A |

| | |
|---|---|
| **Requirement ID:** 1.12<br>**Description:**<br>All teams will be required to use the launch pads provided by Student Launch's launch services provider. No custom pads will be permitted on the launch field. At launch, 8-foot 1010 rails and 12-foot 1515 rails will be provided. The launch rails will be canted 5 to 10 degrees away from the crowd on launch day. The exact cant will depend on launch day wind conditions. | **Verification Plan:** PSP-SL will demonstrate its full scale vehicle's compatibility with the launch pads provided by the launch services provider by launching its full scale vehicle demonstration flight on a 12-foot 1515 launch rail. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

| | |
|---|---|
| **Requirement ID:** 1.13<br>**Description:**<br>Each team must identify a "mentor." A mentor is defined as an adult who is included as a team member, who will be supporting the team (or multiple teams) throughout the project year, and may or may not be affiliated with the school, institution, or organization. The mentor must maintain a current certification, and be in good standing, through the National Association of Rocketry (NAR) or Tripoli Rocketry Association (TRA) for the motor impulse of the launch vehicle and must have flown and successfully recovered (using electronic, staged recovery) a minimum of 2 flights in this or a higher impulse class, prior to PDR. The mentor is designated as the individual owner of the launch vehicle for liability purposes and must travel with the team to launch week. One travel stipend will be provided per mentor regardless of the number of teams he or she supports. The stipend will only be provided if the team passes FRR and the team and mentor attend launch week in April. | **Verification Plan:** Information on PSP-SL's mentor will be provided within project milestone documentation, which will be supplied to the NASA Student Launch team via email. This information will include the mentor's affiliation with NAR and TRA and the mentor's number of level 1, 2, and 3, high-power rocketry flights, as defined by NAR.<br><br>**Comments:** N/A |
| **Status:** Complete | **Verification Test ID:** N/A |

### 6.1.2. Vehicle R&VP

| | |
|---|---|
| **Requirement ID:** 2.1<br>**Description:**<br>The vehicle will deliver the payload to an apogee altitude between 3,500 and 5,500 feet above ground level (AGL). Teams flying below 3,000 feet or above 6,000 feet on Launch Day will be disqualified and receive zero altitude points towards their overall project score. | **Verification Plan:** The altitude will be determined through simulation with open launch vehicle.<br><br>**Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

| | |
|---|---|
| **Requirement ID:** 2.2<br>**Description:**<br>Teams shall identify their target altitude goal at the PDR milestone. The declared target altitude will be used to determine the team's altitude score during Launch Week. | **Verification Plan:** The team will use open rocket calculations to predict out target altitude.<br><br>**Comments:** N/A |
| **Status:** Complete | **Verification Test ID:** N/A |

| | |
|---|---|
| **Requirement ID:** 2.3<br>**Description:**<br>The vehicle will carry one commercially available, barometric altimeter for recording the official altitude used in determining the Altitude Award winner. The Altitude Award will be given to the team with the smallest difference between their measured apogee and their official target altitude on launch | **Verification Plan:** The existence of altimeter will be verified through inspection.<br><br>**Comments:** N/A |

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|---|---|
| day. This altimeter may also be used for deployment purposes (see Requirement 3.4) | |
| **Status:** Complete | **Verification Test ID:** N/A |

| | |
|---|---|
| **Requirement ID:** 2.4<br>**Description:**<br>The launch vehicle will be designed to be recoverable and reusable. Reusable is defined as being able to launch again on the same day without repairs or modifications. | **Verification Plan:** The team will reuse the launch vehicle in subscale and full scale test flights.<br>**Comments:** N/A |
| Status: Incomplete | **Verification Test ID:** C_01 |

| | |
|---|---|
| **Requirement ID:** 2.5<br>**Description:**<br>The launch vehicle will have a maximum of four (4) independent sections. An independent section is defined as a section that is either tethered to the main vehicle or is recovered separately from the main vehicle using its own parachute. | **Verification Plan:** The team will demonstrate that there are no more than 4 independent sections.<br>**Comments:** N/A |
| **Status:** Complete | **Verification Test ID:** N/A |

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|---|---|
| **Requirement ID:** 2.5.1<br>**Description:**<br>Coupler/airframe shoulders which are located at in-flight separation points will be at least 1 body diameter in length. | **Verification Plan:** The team will measure and make sure the coupler/airframe shoulders that are located at in-flight separation points are at least 1 body diameter in length.<br>**Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

| | |
|---|---|
| **Requirement ID:** 2.5.2<br>**Description:**<br>Nosecone shoulders which are located at in-flight separation points will be at least ½ body diameter in length. | **Verification Plan:** The team will measure and make sure the nosecone shoulders that are located at in-flight separation points are at least 1 body diameter in length.<br>**Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

| | |
|---|---|
| **Requirement ID:** 2.6<br>**Description:**<br>The launch vehicle will be capable of being prepared for flight at the launch site within 2 hours of the time | **Verification Plan:** The preparation time of the launch vehicle will be verified through ground testing.<br>**Comments:** N/A |

| | |
|---|---|
| the Federal Aviation Administration flight waiver opens. | |
| **Status:** Incomplete | **Verification Test ID:** N/A |

| | |
|---|---|
| **Requirement ID:** 2.7<br>**Description:**<br>The launch vehicle and payload will be capable of remaining in launch-ready configuration on the pad for a minimum of 2 hours without losing the functionality of any critical on-board components, although the capability to withstand longer delays is highly encouraged. | **Verification Plan:** Ability of the vehicle and payload to remain in launch-ready configuration will be verified by ground testing. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** C_02 |

| | |
|---|---|
| **Requirement ID:** 2.8<br>**Description:**<br>The launch vehicle will be capable of being launched by a standard 12-volt direct current firing system. The firing system will be provided by the NASA-designated launch services provider. | **Verification Plan:** The team will test the system and make sure the launch vehicle can be launched. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

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|---|---|
| **Requirement ID:** 2.9<br>**Description:**<br>The launch vehicle will require no external circuitry or special ground support equipment to initiate launch (other than what is provided by the launch services provider). | **Verification Plan:** Ability to launch without external circuitry or special ground support will be achieved by electronic testing and subscale flight(s). |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

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| **Requirement ID:** 2.10<br>**Description:**<br>The launch vehicle will use a commercially available solid motor propulsion system using ammonium perchlorate composite propellant (APCP) which is approved and certified by the National Association of Rocketry(NAR), Tripoli RocketryAssociation (TRA), and/or the Canadian Association of Rocketry (CAR). | **Verification Plan:** Use of required solid motor propulsion system will be achieved by inspection and demonstration. |
| | **Comments:** N/A |
| **Status:** Complete | **Verification Test ID:** N/A |

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| **Requirement ID:** 2.10.1<br>**Description:**<br>Final motor choice will be declared by the Critical Design Review (CDR) milestone. | **Verification Plan:** The team will demonstrate that the team has the final motor choice by showing it in CDR. |
| | **Comments:** N/A |
| **Status**: Incomplete | **Verification Test ID:** N/A |

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| **Requirement ID:** 2.10.2<br>**Description:**<br>Any motor change after CDR must be approved by the NASA Range Safety Officer (RSO) and will only be approved if the change is for the sole purpose of increasing the safety margin. A penalty against the team's overall score will be incurred when a motor change is made after the CDR milestone, regardless of the reason. | **Verification Plan:** The team will demonstrate that the team has changed motor in future documentation and ensure that it is approved by the NASA RSO. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

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|---|---|
| **Requirement ID:** 2.11<br>**Description:**<br>The launch vehicle will be limited to a single stage. | **Verification Plan:** Limitation of a single stage in launch vehicle will be verified by inspection. |
| | **Comments:** N/A |
| **Status:** Complete | **Verification Test ID:** N/A |

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|---|---|
| **Requirement ID:** 2.12<br>**Description:**<br>The total impulse provided by a College or University launch vehicle will not exceed 5,120 Newton-seconds (L-class). The total impulse provided by a High School or Middle School launch vehicle will not exceed 2,560 Newton-seconds (K-class). | **Verification Plan:** Total impulse will be verified by consulting specifications provided by the manufacturer of the solid rocket motor. |
| | **Comments:** N/A |
| **Status:** Complete | **Verification Test ID:** N/A |

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|---|---|
| **Requirement ID:** 2.13.1<br>**Description:**<br>The minimum factor of safety (Burst or Ultimate pressure versus Max Expected Operating Pressure) will be 4:1 with supporting design documentation included in all milestone reviews. | **Verification Plan:** Use of minimum 4:1 safety factor will be verified through inspection (safety factor will appear in the calculation to determine max expected altitude. |
| | **Comments:** N/A |
| ***Status:*** *Incomplete* | **Verification Test ID:** C_03 |

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| **Requirement ID:** 2.13.2<br>**Description:**<br>Each pressure vessel will include a pressure relief valve that sees the full pressure of the tank and is capable of withstanding the maximum pressure and flow rate of the tank. | **Verification Plan:** N/A<br><br>**Comments:** There is no pressure tank in the current design of the vehicle, therefore this requirement does not apply. |
| **Status:** N/A | **Verification Test ID:** N/A |

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|---|---|
| **Requirement ID:** 2.13.3<br>**Description:**<br>The full pedigree of the tank will be described, including the application for which the tank was designed and the history of the tank. This will include the number of pressure cycles put on the tank, the dates of pressurization/depressurization, and the name of the person or entity administering each pressure event. | **Verification Plan:** N/A<br><br>**Comments:** There is no pressure tank in the current design of the vehicle, therefore this requirement does not apply. |
| **Status:** N/A | **Verification Test ID:** N/A |

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|---|---|
| **Requirement ID:** 2.14<br>**Description:**<br>The launch vehicle will have a minimum static stability margin of 2.0 at the point of rail exit. Rail exit is defined at the point where the forward rail button loses contact with the rail. | **Verification Plan:** The minimum static stability will be verified by measuring the axial distance between the center of gravity and the center of pressure of the vehicle.<br><br>**Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

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|---|---|
| **Requirement ID:** 2.15<br>**Description:**<br>Any structural protuberance on the launch vehicle will be located aft of the burnout center of gravity. | **Verification Plan:** The team will verify this by doing open launch vehicle simulation and calculation.<br><br>**Comments:** N/A |
| **Status:** Complete | **Verification Test ID:** N/A |

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|---|---|
| **Requirement ID:** 2.16<br>**Description:**<br>The launch vehicle will accelerate to a minimum velocity of 52 fps at rail exit. | **Verification Plan:** The minimum velocity will be verified through OpenRocket simulations and the vehicle demonstration test flight.<br><br>**Comments:** N/A |

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| **Status:** Incomplete | **Verification Test ID:** N/A |

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| **Requirement ID:** 2.17<br>**Description:**<br>All teams will successfully launch and recover a subscale model of their launch vehicle prior to CDR. Subscales are not required to be high power launch vehicles. | **Verification Plan:** The team will demonstrate that the team has completed a launch successfully by showing proof in CDR. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

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| **Requirement ID:** 2.17.1<br>**Description:**<br>The subscale model should resemble and perform as similarly as possible to the full-scale model, however, the full-scale will not be used as the subscale model. | **Verification Plan:** The team will scale the full size model down and use extra weight to resemble the full-scale model. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

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|---|---|
| **Requirement ID:** 2.17.2<br>**Description:**<br>The subscale model will carry an altimeter capable of recording the model's apogee altitude. | **Verification Plan:** The team will inspect and make sure a capable altimeter is installed. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

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| **Requirement ID:** 2.17.3<br>**Description:**<br>The subscale launch vehicle must be a newly constructed launch vehicle, designed and built specifically for this year's project. | **Verification Plan:** The team will demonstrate and make sure it is newly built. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

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|---|---|
| **Requirement ID:** 2.17.4<br>**Description:**<br>Proof of a successful flight shall be supplied in the CDR report. Altimeter data output may be used to meet this requirement. | **Verification Plan:** The team will demonstrate that the team has made a successful flight. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

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|---|---|
| **Requirement ID:** 2.18.1<br>**Description:**<br>Vehicle Demonstration Flight - All teams will successfully launch and recover their full-scale launch vehicle prior to FRR in its final flight configuration. The launch vehicle flown must be the same launch vehicle to be flown on launch day. | **Verification Plan:** The team will demonstrate and make sure the launch vehicle meets the requirements.<br>**Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

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|---|---|
| **Requirement ID:** 2.18.1.1<br>**Description:**<br>The vehicle and recovery system will have functioned as designed. | **Verification Plan:** The team will verify the functions of vehicle and recovery system through test flight demonstration.<br>**Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

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| **Requirement ID:** 2.18.1.2<br>**Description:**<br>The full-scale launch vehicle must be a newly constructed launch vehicle, designed and built specifically for this year's project. | **Verification Plan:** The team will demonstrate and make sure the launch vehicle is newly designed and built.<br>**Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

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| **Requirement ID:** 2.18.1.3<br>**Description:**<br>The payload does not have to be flown during the full-scale Vehicle Demonstration Flight. | **Verification Plan:** N/A<br>**Comments:** N/A |
| **Status:** N/A | **Verification Test ID:** N/A |

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| **Requirement ID:** 2.18.1.3.1<br>**Description:**<br>If the payload is not flown, mass simulators will be used to simulate the payload mass. | **Verification Plan:** The team will inspect to make sure the mass simulator is used.<br>**Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

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| **Requirement ID:** 2.18.1.3.2<br>**Description:** | **Verification Plan:** The team will analyze and verify that they are in the same approximate locations. |

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| The mass simulators will be located in the same approximate location on the launch vehicle as the missing payload mass. | **Comments:** N/A |
| Status: Incomplete | **Verification Test ID:** N/A |

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| **Requirement ID:** 2.18.1.4<br>**Description:**<br>If the payload changes the external surfaces of the launch vehicle (such as with camera hous- ings or external probes) or manages the total energy of the vehicle, those systems will be active during the full-scale Vehicle Demonstration Flight. | **Verification Plan:** The team will inspect and make sure the systems are active during demonstration flight.<br>**Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

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|---|---|
| **Requirement ID:** 2.18.1.5<br>**Description:**<br>Teams shall fly the launch day motor for the Vehicle Demonstration Flight. The team may request a waiver for the use of an alternative motor in advance if the home launch field cannot support the full impulse of the launch day motor or in other extenuating circumstances (such as weather). | **Verification Plan:** The team will make sure the motor is the launch day motor by inspecting the motor.<br>**Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

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| **Requirement ID:** 2.18.1.6<br>**Description:**<br>The vehicle must be flown in its fully ballasted configuration during the full-scale test flight. Fully ballasted refers to the same amount of ballast that will be flown during the launch day flight. Additional ballast may not be added without a re-flight of the full-scale launch vehicle. | **Verification Plan:** The team will do calculations and analyze data and make sure the vehicle is flown in its fully ballasted configuration.<br>**Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

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|---|---|
| **Requirement ID:** 2.18.1.7<br>**Description:**<br>After successfully completing the full-scale demonstration flight, the launch vehicle or any of its components will not be modified without the concurrence of the NASA Range Safety Officer (RSO). | **Verification Plan:** The team will inspect and make sure nothing is being modified regularly.<br>**Comments:** N/A |
| Status: Incomplete | **Verification Test ID:** N/A |

| Requirement | Verification |
| --- | --- |
| **Requirement ID:** 2.18.1.8<br>**Description:**<br>Proof of a successful flight shall be supplied in the FRR report. Altimeter data output is required to meet this requirement. | **Verification Plan:** The team will demonstrate that a successful flight occurred in the FRR report.<br><br>**Comments:** N/A |
| Status: Incomplete | **Verification Test ID:** N/A |

| Requirement | Verification |
| --- | --- |
| **Requirement ID:** 2.18.1.9<br>**Description:**<br>Vehicle Demonstration flights must be completed by the FRR submission deadline. No exceptions will be made. If the Student Launch office determines that a Vehicle Demonstration Re-flight is necessary, then an extension may be granted. THIS EXTENSION IS ONLY VALID FOR RE-FLIGHTS, NOT FIRST TIME FLIGHTS. Teams completing a required re-flight must submit an FRR Addendum by the FRR Addendum deadline. | **Verification Plan:** The team will demonstrate that a successful flight has occurred.<br><br>**Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

| Requirement | Verification |
| --- | --- |
| **Requirement ID:** 2.18.2<br>**Description:**<br>Payload Demonstration Flight - All teams will successfully launch and recover their full-scale launch vehicle containing the completed payload prior to the Payload Demonstration Flight deadline. The launch vehicle flown must be the same launch vehicle to be flown on launch day. The purpose of the Payload Demonstration Flight is to prove the launch vehicle's ability to safely retain the constructed payload during flight and to show that all aspects of the payload perform as designed. A successful flight is defined as a launch in which the launch vehicle experiences stable ascent and the payload is fully retained until it is deployed (if applicable) as designed. | **Verification Plan:** The team will demonstrate that the vehicle can be successfully flown with the completed payload.<br><br>**Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

| Requirement | Verification |
| --- | --- |
| **Requirement ID:** 2.18.2.1<br>**Description:**<br>The payload must be fully retained until the intended point of deployment (if applicable), all retention mechanisms must function as designed, and the retention mechanism must not sustain damage requiring repair. | **Verification Plan:** The team will demonstrate this through a successful payload demonstration flight.<br><br>**Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

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| **Requirement ID:** 2.18.2.2<br>**Description:**<br>The payload flown must be the final, active version. | **Verification Plan:** The team will verify that the payload flown is the final version by inspecting the payload. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

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| **Requirement ID:** 2.18.2.3<br>**Description:**<br>If requirements 2.18.2.1 and 2.18.2.2 are met during the original Vehicle Demonstration Flight, occurring prior to the FRR deadline and the information is included in the FRR package, the additional flight and FRR Addendum are not required. | **Verification Plan:** N/A |
| | **Comments:** N/A |
| **Status:** N/A | **Verification Test ID:** N/A |

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| **Requirement ID:** 2.18.2.4<br>**Description:**<br>Payload Demonstration Flights must be completed by the FRR Addendum deadline. NO EXTENSIONS WILL BE GRANTED. | **Verification Plan:** The team will show that the payload demonstration flight has been completed by showing proof in FRR. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

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| **Requirement ID:** 2.19<br>**Description:**<br>An FRR Addendum will be required for any team completing a Payload Demonstration Flight or NASA required Vehicle Demonstration Re-flight after the submission of the FRR Report. | **Verification Plan:** The team will submit an FRR Addendum for re-flight after submitting FRR report. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

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|---|---|
| **Requirement ID:** 2.19.1<br>**Description:**<br>Teams required to complete a Vehicle Demonstration Re-Flight and failing to submit the FRR Addendum by the deadline will not be permitted to fly the vehicle at launch week. | **Verification Plan:** N/A |
| | **Comments:** N/A |
| **Status:** N/A | **Verification Test ID:** N/A |

| Requirement | Verification |
|---|---|
| **Requirement ID:** 2.19.2<br>**Description:**<br>Teams who successfully complete a Vehicle Demonstration Flight but fail to qualify the payload by satisfactorily completing the Payload Demonstration Flight requirement will not be permitted to fly the payload at launch week. | **Verification Plan:**<br><br>**Comments:** N/A |
| **Status:** N/A | **Verification Test ID:** N/A |

| Requirement | Verification |
|---|---|
| **Requirement ID:** 2.19.3<br>**Description:**<br>Teams who complete a Payload Demonstration Flight which is not fully successful may petition the NASA RSO for permission to fly the payload at launch week. Permission will not be granted if the RSO or the Review Panel have any safety concerns. | **Verification Plan:** N/A<br><br>**Comments:** N/A |
| **Status:** N/A | **Verification Test ID:** N/A |

| Requirement | Verification |
|---|---|
| **Requirement ID:** 2.20<br>**Description:**<br>The team's name and launch day contact information shall be in or on the launch vehicle airframe as well as in or on any section of the vehicle that separates during flight and is not tethered to the main airframe. This information shall be included in a manner that allows the information to be retrieved without the need to open or separate the vehicle. | **Verification Plan:** The team will inspect and make sure all required information exist on parts.<br><br>**Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

| Requirement | Verification |
|---|---|
| **Requirement ID:** 2.21<br>**Description:**<br>All Lithium Polymer batteries will be sufficiently protected from impact with the ground and will be brightly colored, clearly marked as a fire hazard, and easily distinguishable from other payload hardware. | **Verification Plan:** The team will inspect the placement and visuals of lithium polymer batteries to ensure this requirement is met.<br><br>**Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

| Requirement | Verification |
|---|---|
| **Requirement ID:** 2.22.1<br>**Description:**<br>The launch vehicle will not utilize forward canards. Camera housings will be exempted, provided the team can show that the housing(s) causes minimal aerodynamic effect on the launch vehicle's stability. | **Verification Plan:** Absence of forward canards will be verified through inspection and demonstration.<br><br>**Comments:** N/A |

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| **Status:** Incomplete | **Verification Test ID:** N/A |

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| **Requirement ID:** 2.22.2<br>**Description:**<br>The launch vehicle will not utilize forward firing motors. | **Verification Plan:** Absence of forward firing motors will be verified through inspection and demonstration. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

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|---|---|
| **Requirement ID:** 2.22.3<br>**Description:**<br>The launch vehicle will not utilize motors that expel titanium sponges (Sparky, Skidmark, Metal-Storm, etc.) | **Verification Plan:** Absence of prohibited motors will be verified through demonstration at the vehicle demonstration flight. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

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|---|---|
| **Requirement ID:** 2.22.4<br>**Description:**<br>The launch vehicle will not utilize hybrid motors. | **Verification Plan:** Absence of hybrid motors will be verified through demonstration at the vehicle demonstration flight. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

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|---|---|
| **Requirement ID:**2.22.5<br>**Description:**<br>The launch vehicle will not utilize a cluster of motors. | **Verification Plan:** Absence of a cluster of motors will be verified through inspection and demonstration. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

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|---|---|
| **Requirement ID:** 2.22.6<br>**Description:**<br>The launch vehicle will not utilize friction fitting for motors. | **Verification Plan:** Absence of friction fitting will be verified through inspection. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

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| **Requirement ID:** 2.22.7<br>**Description:** | **Verification Plan:** The team will use calculation and open launch vehicle simulation to verify the max speed does not exceed Mach 1. |

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| The launch vehicle will not exceed Mach 1 at any point during flight. | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

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| **Requirement ID:** 2.22.8<br>**Description:**<br>Vehicle ballast will not exceed 10% of the total unballasted weight of the launch vehicle as it would sit on the pad (i.e. a launch vehicle with an unballasted weight of 40lbm. on the pad may contain a maximum of 4lbm. of ballast). | **Verification Plan:** The team will verify this using calculation.<br>**Comments:** N/A |
| **Status**: Incomplete | **Verification Test ID:** N/A |

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|---|---|
| **Requirement ID:** 2.22.9<br>**Description:**<br>Transmissions from onboard transmitters will not exceed 250 mW of power (per transmitter). | **Verification Plan:** The team will calculate and make sure that the transmission will not exceed 250mW.<br>**Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

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| **Requirement ID:** 2.22.10<br>**Description:**<br>Transmitters will not create excessive interference. Teams will utilize unique frequencies, hand- shake/passcode systems, or other means to mitigate interference caused to or received from other teams. | **Verification Plan:** The team will test and calculate to make sure that the transmitter does not create excessive interference.<br>**Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** C_04 |

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|---|---|
| **Requirement ID:** 2.22.11<br>**Description:**<br>Excessive and/or dense metal will not be utilized in the construction of the vehicle. Use of lightweight metal will be permitted but limited to the amount necessary to ensure structural integrity of the airframe under the expected operating stresses. | **Verification Plan:** The team will inspect and calculate to make sure the usage of metal is within standard.<br>**Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

### 6.1.3. Avionics & Recovery R&VP

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| **Requirement ID:** 3.1<br>**Description:**<br>The launch vehicle will stage the deployment of its recovery devices, where a drogue parachute is deployed at apogee, and a main parachute is deployed at a lower altitude. Tumble or streamer recovery from apogee to main parachute deployment is also permissible, provided that kinetic energy during drogue stage descent is reasonable, as deemed by the RSO. | **Verification Plan:** Having these components will be verified via inspection.<br><br>**Comments:** N/A |
| **Status:** Complete | **Verification Test ID:** N/A |

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| **Requirement ID:** 3.1.1<br>**Description:**<br>The main parachute shall be deployed no lower than 500 feet. | **Verification Plan:** The parachute will be deployed at 800 feet to ensure that by the time it reaches 500 feet, it is fully open.<br><br>**Comments:** N/A |
| **Status:** Complete | **Verification Test ID:** A_01 |

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|---|---|
| **Requirement ID:** 3.1.2<br>**Description:**<br>The apogee event may contain a delay of no more than 2 seconds. | **Verification Plan:** This will be verified through subscale and full scale launches.<br><br>**Comments:** N/A |
| **Status:** Complete | **Verification Test ID:** N/A |

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| **Requirement ID:** 3.1.3<br>**Description:**<br>Motor ejection is not a permissible form of primary or secondary deployment. | **Verification Plan:** The PSP-SL team will not eject any motor it uses, and this will be verified through subscale and full scale launches.<br><br>**Comments:** N/A |
| **Status:** Complete | **Verification Test ID:** N/A |

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| **Requirement ID:** 3.2<br>**Description:**<br>Each team must perform a successful ground ejection test for both the drogue and main parachutes prior to the initial subscale and full-scale launches. | **Verification Plan:** At least six feet of separation of the avionics bay from the corresponding airframe, as well as full ejection of the corresponding parachute, must be achieved from each black powder charge.<br><br>**Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** A_02 |

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|---|---|
| **Requirement ID:** 3.3<br>**Description:**<br>Each independent section of the launch vehicle will have a maximum kinetic energy of 75 ft-lbf at landing. | **Verification Plan:** After the main parachute is dropped from an already opened state, the calculated kinetic energy of the largest section of the launch vehicle will be calculated. |
| | **Comments:** N/A |
| **Status:** Complete | **Verification Test ID:** N/A |

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| **Requirement ID:** 3.4<br>**Description:**<br>The recovery system will contain redundant, commercially available altimeters. The term "altimeters" includes both simple altimeters and more sophisticated flight computers. | **Verification Plan:** Having these components will be verified via inspection. |
| | **Comments:** N/A |
| **Status:** Complete | **Verification Test ID:** N/A |

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|---|---|
| **Requirement ID:** 3.5<br>**Description:**<br>Each altimeter will have a dedicated power supply, and all recovery electronics will be powered by commercially available batteries. | **Verification Plan:** Having these components will be verified via inspection. |
| | **Comments:** N/A |
| **Status:** Complete | **Verification Test ID:** N/A |

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| **Requirement ID:** 3.6<br>**Description:**<br>Each altimeter will be armed by a dedicated mechanical arming switch that is accessible from the exterior of the launch vehicle airframe when the launch vehicle is in the launch configuration on the launch pad. | **Verification Plan:** Accessibility will be verified through subscale and full scale launches. |
| | **Comments:** N/A |
| **Status:** Complete | **Verification Test ID:** N/A |

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| **Requirement ID:** 3.7<br>**Description:**<br>Each arming switch will be capable of being locked in the ON position for launch (i.e. cannot be disarmed due to flight forces). | **Verification Plan:** This will be verified through subscale and full scale launches. |
| | **Comments:** N/A |
| **Status:** Complete | **Verification Test ID:** N/A |

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| **Requirement ID:** 3.8<br>**Description:**<br>The recovery system electrical circuits will be completely independent of any payload electrical circuits. | **Verification Plan:** Independence will be verified via inspection.<br><br>**Comments:** N/A |
| **Status:** Complete | **Verification Test ID:** N/A |

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| **Requirement ID:** 3.9<br>**Description:**<br>Removable shear pins will be used for both the main parachute compartment and the drogue parachute compartment. | **Verification Plan:** The use of shear pins will be verified through inspection.<br><br>**Comments:** N/A |
| **Status:** Complete | **Verification Test ID:** N/A |

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|---|---|
| **Requirement ID:** 3.10<br>**Description:**<br>The recovery area will be limited to 2,500 ft. radius from the launch pads. | **Verification Plan:** This will be verified through subscale and full scale launches.<br><br>**Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

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|---|---|
| **Requirement ID:** 3.11<br>**Description:**<br>Descent time will be limited to 90 seconds (apogee to touch down). | **Verification Plan:** This will be verified through subscale and full scale launches.<br><br>**Comments:** N/A |
| **Status:** Complete | **Verification Test ID:** N/A |

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| **Requirement ID:** 3.12<br>**Description:**<br>An electronic tracking device will be installed in the launch vehicle and will transmit the position of the tethered vehicle or any independent section to a ground receiver. | **Verification Plan:** This will be verified through subscale and full scale launches.<br><br>**Comments:** N/A |
| **Status:** Complete | **Verification Test ID:** N/A |

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| **Requirement ID:** 3.12.1<br>**Description:**<br>Any launch vehicle section or payload component, which lands untethered to the launch vehicle, will | **Verification Plan:** Having these components will be verified via inspection. |

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| contain an active electronic tracking device. | **Comments:** N/A |
| **Status:** Complete | **Verification Test ID:** N/A |

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| **Requirement ID:** 3.12.2<br>**Description:**<br>The electronic tracking device(s) will be fully functional during the official flight on launch day. | **Verification Plan:** The functionality of the tracking devices will be verified through subscale and full scale launches. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

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|---|---|
| **Requirement ID:** 3.13<br>**Description:**<br>The recovery system electronics will not be adversely affected by any other on-board electronic devices during flight (from launch until landing). | **Verification Plan:** This will be verified via ground testing with all other electronic components mounted into the rocket and running to ensure the avionics system does not experience interference. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** A_03 |

| | |
|---|---|
| **Requirement ID:** 3.13.1<br>**Description:**<br>The recovery system altimeters will be physically located in a separate compartment within the vehicle from any other radio frequency transmitting device and/or magnetic wave producing device. | **Verification Plan:** This will be verified via inspection. |
| | **Comments:** N/A |
| **Status:** Complete | **Verification Test ID:** N/A |

| | |
|---|---|
| **Requirement ID:** 3.13.2<br>**Description:**<br>The recovery system electronics will be shielded from all onboard transmitting devices to avoid inadvertent excitation of the recovery system electronics. | **Verification Plan:** This will be verified via inspection. |
| | **Comments:** N/A |
| **Status:** Complete | **Verification Test ID:** N/A |

| | |
|---|---|
| **Requirement ID:** 3.13.3<br>**Description:**<br>The recovery system electronics will be shielded from all onboard devices which may generate magnetic waves (such as generators, solenoid valves, and Tesla coils) to avoid inadvertent | **Verification Plan:** This will be verified via inspection. |
| | **Comments:** N/A |

| | |
|---|---|
| excitation of the recovery system. | |
| **Status:** Complete | **Verification Test ID:** N/A |

| | |
|---|---|
| **Requirement ID:** 3.13.4<br>**Description:**<br>The recovery system electronics will be shielded from any other onboard devices which may adversely affect the proper operation of the recovery system electronics. | **Verification Plan:** This will be verified via inspection.<br><br>**Comments:** N/A |
| **Status:** Complete | **Verification Test ID:** N/A |

### 6.1.4. Payload R&VP

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|---|---|
| **Requirement ID:** 4.1<br>**Description:**<br>High school and middle school teams are required to either design their own science or engineering experiment or choose to complete the college/university payload mission. | **Verification Plan:** N/A<br><br>**Comments:** Does not apply to PSP-SL, as PSP-SL is a university-level team. |
| **Status:** N/A | **Verification Test ID:** N/A |

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|---|---|
| **Requirement ID:** 4.2<br>**Description:**<br>The team will design a UAV payload that will safely be carried by a high powered launch vehicle. The UAV will deploy from the launch vehicle and recover simulated lunar ice. The UAV will be designed to be safe and follow all rules and regulations. | **Verification Plan:** The UAV will undergo a series of testing and simulations that will validate the capability of the UAV to complete a successful ice sample recovery. These tests will validate that the UAV can functionally perform every mission function on its own as well as in sequence. In addition, all safety critical structural components used on the UAV and UAV retention system will be designed to have a safety factor of at least two using FEA.<br><br>**Comments:** Testing and simulation of the UAV will include a series of ground and flight testing that measure performance, measure flight-time, validate component integration, and test autonomous software. |
| **Status:** Incomplete | **Verification Test ID:** P_01 |

| | |
|---|---|
| **Requirement ID:** 4.3.1<br>**Description:**<br>The launch vehicle will be launched from the NASA-designated launch area using the | **Verification Plan:** The payload on the launch vehicle will be designed to contain all the hardware necessary for mission completion, All manipulation and control of the payload post recovery will be done through wireless commands issued from the GCS. |

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| provided launch pad. All hardware utilized at the recovery must launch on the vehicle. | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

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|---|---|
| **Requirement ID:** 4.3.2<br>**Description:**<br>The team will be able to recover ice samples from five different recovery areas with each recovery site being 3 feet in diameter and contain sample material extending to at least 2 inches below the surface. | **Verification Plan:** The UAV will be tested in simulation and in a makeshift sampling area to confirm that the UAV will be able to detect, track, and extract and ice sample from a recovery area. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** P_02 |

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|---|---|
| **Requirement ID:** 4.3.3<br>**Description:**<br>The recovered ice sample will be a minimum of 10 milliliters (mL). | **Verification Plan:** The UAV ice mining and procurement system will be tested to mine and contain at least 10mL of ice. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** P_03 |

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|---|---|
| **Requirement ID:** 4.3.4<br>**Description:**<br>Once the sample is recovered, it must be stored and transported at least 10 linear feet from the recovery area. | **Verification Plan:** The UAV will be tested to fly 10 linear feet away from the recovery site at full ice capacity. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

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|---|---|
| **Requirement ID:** 4.3.5<br>**Description:**<br>The team must abide by all FAA and NAR rules and regulations. | **Verification Plan:** The operation of the UAV will abide by any and all rules and regulations from the FAA and NAR applicable to the operation of model aircraft. In addition, the operation of the UAV will follow any rules regulations issued by state and other local governments. |
| | **Comments:** Verification must be completed once UAV is constructed. |
| **Status:** Incomplete | **Verification Test ID:** N/A |

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|---|---|
| **Requirement ID:** 4.3.6<br>**Description:**<br>Black powder and/or similar energetics are only permitted for deployment of in-flight recovery systems. And ground systems must employ mechanical systems. | **Verification Plan:** The deployment used for the payload will be designed to not incorporate the use of energetics, but will strictly employ the use of a mechanical systems.<br><br>**Comments:** N/A |
| **Status:** Complete | **Verification Test ID:** N/A |

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|---|---|
| **Requirement ID:** 4.3.7<br>**Description:**<br>Any part of the payload or vehicle that is designed to be deployed, whether on the ground or in the air, must be fully retained until it is deployed as designed. | **Verification Plan:** The ground-deployed payload will be retained and locked in the vehicle until a signal is sent from the GCS.<br><br>**Comments:** N/A |
| **Status:** Complete | **Verification Test ID:** N/A |

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|---|---|
| **Requirement ID:** 4.3.7.1<br>**Description:**<br>A mechanical retention system will be designed to prohibit premature deployment. | **Verification Plan:** The retention and deployment system will strictly make use of a mechanical system to retain and deploy the UAV.<br><br>**Comments:** N/A |
| **Status:** Complete | **Verification Test ID:** N/A |

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|---|---|
| **Requirement ID:** 4.3.7.2<br>**Description:**<br>The retention system will be robust enough to successfully endure flight forces experienced during both typical and atypical flights. | **Verification Plan:** The retention system will be tested to validate a robust design and construction, and any structurally critical components will be designed with a safety factor of at least 2.<br><br>**Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** P_04 |

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|---|---|
| **Requirement ID:** 4.3.7.3<br>**Description:**<br>The designed retention system will be fail-safe. | **Verification Plan:** The mechanical system employed to retain the payload in-flight will be fail-safe and will be shown to function regardless of power delivery. |

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| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** P_05 |

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|---|---|
| **Requirement ID:** 4.3.7.4<br>**Description:**<br>Exclusive use of shear pins will not meet requirement 4.3.7. | **Verification Plan:** Shear pins will not be used for the retention of the payload. |
| | **Comments:** N/A |
| **Status:** Complete | **Verification Test ID:** N/A |

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|---|---|
| **Requirement ID:** 4.4.1<br>**Description:**<br>Any experiment element that is jettisoned during the recovery phase will receive real-time RSO permission prior to initiating the jettison event. | **Verification Plan:** N/A |
| | **Comments:** The UAV will not be jettisoned during the recovery phase and will not require real-time RSO permission. |
| **Status:** N/A | **Verification Test ID:** N/A |

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|---|---|
| **Requirement ID:** 4.4.2<br>**Description:**<br>The UAV, if designed to be deployed during descent, will be tethered to the vehicle with a remotely controlled release mechanism until the RSO has given permission to release the UAV. | **Verification Plan:** N/A |
| | **Comments:** The UAV is not be designed to be deployed during flight and therefore will not require a remotely controlled release mechanism that will be triggered during descent. |
| **Status:** N/A | **Verification Test ID:** N/A |

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|---|---|
| **Requirement ID:** 4.4.3<br>**Description:**<br>Teams flying UAVs will abide by all applicable FAA regulations, including the FAA's Special Rule for Model Aircraft. | **Verification Plan:** The operation of the UAV shall follow all laws laid out by the FAA pertaining to the operation of rotorcraft and model aircraft. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

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|---|---|
| **Requirement ID:** 4.4.4<br>**Description:** | **Verification Plan:** The UAV, once constructed, will be registered with the FAA and its registration number will be clearly marked on the outside of the vehicle. |

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|---|---|
| Any UAV weighing more than .55lbm. will be registered with the FAA and the registration number marked on the vehicle. | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

### 6.1.5. Safety R&VP

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|---|---|
| **Requirement ID:** 5.1<br>**Description:**<br>Each team will use a launch and safety checklist. The final checklists will be included in the FRR report and used during the Launch Readiness Review (LRR) and any launch day operations. | **Verification Plan:** Design review documents will be inspected to contain a launch checklist encompassing at least Pre-Launch, Launch, and Post Launch operations.<br><br>**Comments:** N/A |
| **Status:** Complete | **Verification Test ID:** N/A |

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|---|---|
| **Requirement ID:** 5.2<br>**Description:**<br>Each team must identify a student safety officer who will be responsible for all requirements under the “5.3” designation. | **Verification Plan:** A safety officer will be voted on before the competition season.<br><br>**Comments:** The team safety officer for 2019-2020 is Noah Stover. |
| **Status:** Complete | **Verification Test ID:** N/A |

| | |
|---|---|
| **Requirement ID:** 5.3.1<br>**Description:**<br>Monitor team activities with an emphasis on safety during the design of vehicle and payload, the construction of vehicle and payload components, the assembly of vehicle and payload, the ground testing of vehicle and payload, the subscale launch test(s), the full-scale launch test(s), the launch day, the recovery activities, and the STEM engagement activities. | **Verification Plan:** The safety officer will be held accountable by record of attendance by the heads of operations for construction and testing procedures, and the project manager for launch operations.<br><br>**Comments:** This requirement is in progress. |
| **Status:** Incomplete | **Verification Test ID:** N/A |

| | |
|---|---|
| **Requirement ID:** 5.3.2<br>**Description:** | **Verification Plan:** Safety plans will be put in place for the operations of construction (machine operations, epoxy application, etc), launch (see 5.1), and vehicle recovery. |

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| Implement procedures developed by the team for construction, assembly, launch, and recovery activities. | **Comments:** This requirement is in progress. |
| **Status:** Incomplete | **Verification Test ID:** N/A |

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|---|---|
| **Requirement ID:** 5.3.3<br>**Description:**<br>Manage and maintain current revisions of the team's hazard analyses, failure modes analysis, procedures, and MSDS/chemical inventory data. | **Verification Plan:** Look over risks from previous projects and check up with other sub teams to stay updated on other possible risks.<br>**Comments:** For PDR, the safety subteam used past risks from previous years' projects as a baseline to build the current project's risk analysis. |
| **Status:** Incomplete | **Verification Test ID:** N/A |

| | |
|---|---|
| **Requirement ID:** 5.3.4<br>**Description:**<br>Assist in the writing and development of the team's hazard analyses, failure models analysis, and procedures. | **Verification Plan:** Safety data will be reviewed before each milestone document submission and be updated accordingly.<br>**Comments:** The safety subteam gathered before PDR submission to write and formulate risks and how to analyse them. |
| **Status:** Incomplete | **Verification Test ID:** N/A |

| | |
|---|---|
| **Requirement ID:** 5.4<br>**Description:**<br>During test flights, teams will abide by the rules and guidance of the local Rocketry club's RSO. The allowance of certain vehicle configurations and/or payloads at the NASA Student Launch does not give explicit or implicit authority for teams to fly those vehicle configurations and/or payloads at other club launches. Teams should communicate their intentions to the local club's President or Prefect and RSO before attending any NAR or TRA launch. | **Verification Plan:** Inform RSO and club president of launch in a reasonable time prior. Obtain permission to use payload in launch if payload is to be used.<br>**Comments:** In order to organize launches PSP-SL will contact necessary administrative heads to ensure the launch requirements are within the safety standards they hold for launches. |
| **Status:** Incomplete | **Verification Test ID:** N/A |

| | |
|---|---|
| **Requirement ID:** 5.5<br>**Description:**<br>Teams will abide by all rules set forth by the FAA. | **Verification Plan:** An extensive review of FAA guidelines and regulations and checking in order to make sure that all subteams follow and stay within the given regulations. |

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|---|---|
| | **Comments:** The safety subteam reviewed FAA guidelines in order to analyze possible risks and their mitigations. Before constructions or launches, PSP-SL will go over guidelines again to make sure the team is following the rules. |
| **Status:** Complete | **Verification Test ID:** N/A |

## 6.2. PSP-SL Team-Derived R&VP

PSP-SL's team-derived requirements follow the same R&VP format as the NASA-derived requirements from the NASA Derived R&VP section. Please observe the information at the beginning of that section on interpreting PSP-SL's R&VP tables to understand the information listed below.

### 6.2.1. Team-Derived General R&VP

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|---|---|
| **Requirement ID:** T1.1<br>**Description:**<br>All milestone documents will be finished by the team at least one week ahead of required deadline; this ensures that the executive board may review and make edits prior to milestone submission. | **Verification Plan:** Subteam leads will ensure that each subteam finishes their respective section prior to this deadline. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

| | |
|---|---|
| **Requirement ID:** T1.2<br>**Description:**<br>Each team member, regardless of position, will miss no more than five meetings throughout the entirety of the competition; this ensures that team members stay actively engaged and are making meaningful contributions to the team's design. | **Verification Plan:** Team will take attendance prior to the start of each meeting |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

| | |
|---|---|
| **Requirement ID:** T1.3<br>**Description:**<br>STEM engagement activity reports will be submitted within a week of activity date so that documentation of even can be properly written. | **Verification Plan:** Social / Outreach team lead will bring activity reports to all outreach events to ensure that team members fill out reports at completion of event. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

| | |
|---|---|
| **Requirement ID:** T1.4<br>**Description:**<br>In order to be eligible to attend launch week, each team member will be required to attend a minimum of three STEM educational outreach events. | **Verification Plan:**<br>Attendance will be taken prior to the start of each team lead STEM outreach event. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

### 6.2.2. Team-Derived Vehicle R&VP

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|---|---|
| **Requirement ID:**<br>T2.1<br>**Description:**<br>The vehicle will carry the payload to an apogee altitude of 4350 +/- 100 feet AGL. | **Verification Plan:**<br>Verification analysis will be performed in OpenRocket, secondary analysis will be performed in RASAero, tertiary analysis will be performed in avionics and recovery trajectory code, and final verification will be gathered from final launch day altimeters |
| | **Comments:** N/A |
| ***Status:*** *Incomplete* | **Verification Test ID:** N/A |

| | |
|---|---|
| **Requirement ID:** T2.2<br>**Description:**<br>The vehicle will be capable of carrying the payload to apogee with a 12.5 pound or less payload. | **Verification Plan:** 12.5 pounds will be included in the mass of simulations performed to account for the mass of the payload. Further verification will be performed from the gathering of altimeter data during final launch. |
| | **Comments:** N/A |
| **Status:** Complete | **Verification Test ID:** N/A |

| | |
|---|---|
| **Requirement ID:** T2.3<br>**Description:**<br>The flight path of the launch vehicle shall not differ from the vertical axis by an observable amount under any circumstances or launch conditions with the exception of the flight path at apogee. | **Verification Plan:** Visual inspection of all launch vehicle test flights during ascent will verify the vehicle's flight path does not vary from the vertical direction by unreasonable amounts. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

| | |
|---|---|
| **Requirement ID:** T2.4<br>**Description:**<br>The vehicle will be capable of successfully deploying the payload system's UAV after landing. | **Verification Plan:** This requirement will be verified by demonstrating payload deployment capabilities of the launch vehicle during the full scale flight or the payload demonstration flight. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

| | |
|---|---|
| **Requirement ID:** T2.5<br>**Description:**<br>The full-scale launch vehicle will be successfully launched and recovered in a test flight before March 1, 2020, configured in the same configuration that will be used on the final launch day | **Verification Plan:** Full scale flight launch data will be recorded and included in milestone documentation to prove a full scale flight has occurred by the specified date and in the desired configuration. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

| | |
|---|---|
| **Requirement ID:** T2.6<br>**Description:**<br>If the launch day motor is not capable of being flown during the full-scale test flight, the replacement motor shall simulate as closely as possible the | **Verification Plan:** The motor which is used to simulate the final motor to be used shall be the closest allowable motor impulse |

| | |
|---|---|
| predicted maximum velocity and maximum acceleration of the launch day flight. | level and shall retain a size and mass which differs by no more than 10% than the motor to be used. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

| | |
|---|---|
| **Requirement ID:** T2.7<br>**Description:**<br>If the Student Launch office determines that a re-flight is necessary, then another flight of the full-scale vehicle will be conducted before March 20, 2020. | **Verification Plan:** Full scale re-flight launch data will be recorded and included in milestone documentation to prove a re-flight has occurred by the specified date. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

### 6.2.3. Team-Derived Avionics & Recovery R&VP

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|---|---|
| **Requirement ID:** T3.1<br>**Description:**<br>The main parachute will open with an altitude great enough for the heaviest section of the launch vehicle to land with a kinetic energy of less than 75 ft-lbf. | **Verification Plan:** After the main parachute is dropped from an already opened state, the calculated kinetic energy of the largest section of the launch vehicle will be calculated. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** AT_1 |

| | |
|---|---|
| **Requirement ID:** T3.2<br>**Description:**<br>Both of the batteries will consistently supply 40-60 mAh to their corresponding altimeter for a minimum of 1.5 hours. | **Verification Plan:** Each battery will be verified if, connected to its corresponding altimeter, the battery is able to keep it powered on for an hour and a half as well as stay within 40 and 60 mAh of electric charge (measured every half hour). |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** AT_2 |

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|---|---|
| **Requirement ID:** T3.3<br>**Description:** | **Verification Plan:** The distance between the avionics bay and each airframe will be measured after ground ejection, |

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| For ground testing, the black powder ejection system will create at least 6 feet of separation between the avionics bay and each airframe for at least one amount of black powder equal to or greater than 4 grams, as well as full ejection of each parachute. | and whether or not the each parachute was fully ejected will be inspected. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** AT_3 |

| | |
|---|---|
| **Requirement ID:** T3.4<br>**Description:**<br>Both altimeters need to be able to consistently ignite both ejection charges at the appropriate times. | **Verification Plan:** Altimeter functionality will be verified through simulating a flight via a vacuum chamber. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** AT_4 |

| | |
|---|---|
| **Requirement ID:** T3.4.1<br>**Description:**<br>The primary drogue ejection charge will ignite within +/- 50 feet of apogee. | **Verification Plan:** Recorded drogue ignition altitude will be compared against apogee altitude. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** AT_4 |

| | |
|---|---|
| **Requirement ID:** T3.4.2<br>**Description:**<br>The redundant drogue ejection charge will have a drogue delay between 0.75 and 1.75 seconds. | **Verification Plan:** The duration of time between apogee and drogue ignition will be measured. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** AT_4 |

| | |
|---|---|
| **Requirement ID:** T3.4.3<br>**Description:**<br>The primary and redundant main ejection charges will ignite within +/- 50 feet of their programmed deployment altitudes (800' AGL for the primary altimeter and 700' AGL for the redundant altimeter). | **Verification Plan:** Recorded main ignition altitudes will be compared against programmed deployment altitudes for each altimeter. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** AT_4 |

| | |
|---|---|
| **Requirement ID:** T3.5<br>**Description:**<br>The altimeter firing sequence will be consistent across temperature extremes. | **Verification Plan:** Each altimeter will be verified if it emits three beeps every five seconds after the initialization routine in both temperature extremes, indicating successful continuity for a dual deploy configuration. |

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| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** AT_5 |

### 6.2.4. Team-Derived Payload R&VP

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|---|---|
| **Requirement ID:** T4.1<br>**Description:**<br>The UAV shall not pose a significant safety risk to its surroundings during operation. | **Verification Plan:** Operation of the UAV will strictly adhere to predetermined flight paths. Any and all safety risks will be identified and addressed prior to flight, and proper documentation of emergency procedures will be available at hand. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

| | |
|---|---|
| **Requirement ID:** T4.2<br>**Description:**<br>Autonomous operation of the UAV shall require a designated pilot in command (PIC) monitoring UAV telemetry and status, and an observer that maintains visual line of sight with the UAV at all times. | **Verification Plan:** Every flight of the UAV will require a designated PIC and observer, both with proper training and equipment. This information will be documented in a UAV operational document that is filled out before every flight. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

| | |
|---|---|
| **Requirement ID:** T4.3<br>**Description:**<br>Control of the UAV with computer vision algorithms shall be minimally accompanied with real-time imaging data and a kill-switch. | **Verification Plan:** Testing of computer vision algorithms on a UAV in-flight will require imaging data to be transmitted and closely monitored by the PIC. A kill-switch will be easily accessible on the GCS. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

| | |
|---|---|
| **Requirement ID:** T4.4<br>**Description:**<br>Switches on the GCS that alter the operation or flight mode of the UAV, are mission critical, or are essential for the safe operation of the UAV will require checkout testing. | **Verification Plan:** Switches will be tested on the ground and in-flight (assuming the test will not risk the safety of the vehicle nor its surroundings) to ensure expected behavior is met. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** PT_04 |

| | |
|---|---|
| **Requirement ID:** T4.5<br>**Description:**<br>The operation of the UAS shall adhere to Purdue's Operating Procedures For Use of UAS and Model Aircraft | **Verification Plan:** The operation of the UAV shall follow all rules laid out by Purdue University pertaining to the operation of UAVs. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

| | |
|---|---|
| **Requirement ID:** T4.6<br>**Description:**<br>The GCS shall be capable of monitoring and controlling the UAV and the R&D system at a range of at least 1 mile to ensure safe operation. | **Verification Plan:** The GCS will undergo range testing to verify that both imaging data, telemetry data, and R&D data can be transmitted at least 1 mile. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** PT_05 |

| | |
|---|---|
| **Requirement ID:** T4.7<br>**Description:**<br>The UAV payload shall not operate above 400ft AGL. | **Verification Plan:** The UAV will have a mechanical switch that isolates power when the UAV is in the launch vehicle such that the UAV will not be powered on during launch vehicle ascent. The UAV will also have a programmed flight envelope well below the FAA 400ft AGL operating ceiling. |
| | **Comments:** Testing will ensure that the mechanical switch being used to isolate the UAV battery does not prematurely trigger. Testing will also be conducted to set limits on AGL flight. |
| **Status:** Incomplete | **Verification Test ID:** PT_06, PT_07 |

| | |
|---|---|
| **Requirement ID:** T4.8<br>**Description:**<br>All electrical equipment in the payload bay that are not directly connected to the UAV battery shall be capable of at least 2 hours of operation. | **Verification Plan:** All components of the payload will undergo power draw testing using flight hardware with the test duration exceeding 2 hours. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** PT_08 |

### 6.2.5. Team-Derived Safety R&VP

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|---|---|
| **Requirement ID:** T5.1<br>**Description:** | **Verification Plan:** Team members will be asked to display Pocket Safety Documents before applicable operations occur. |

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| Every team member must have a Pocket Safety Document on their person for all launch day, construction, assembly, or test operation. | **Comments:** Separate pocket safety documents will be written for the operations of testing, machining, construction, and launch days. |
| **Status:** Incomplete | **Verification Test ID:** N/A |

| | |
|---|---|
| **Requirement ID:** T5.2.1<br>**Description:**<br>Team members must be briefed on machine operations and operational hazards prior to construction operations. | **Verification Plan:** All team members performing machining or other construction operations will be present for a pre-operation briefing presentation covering PPE, machine operation, and other safety hazards approved by the safety officer. |
| | **Comments:** Pocket Safety Documents (See T5.1) will contain a condensed version of pre-operation briefing for on-site reference. |
| **Status:** Incomplete | **Verification Test ID:** N/A |

| | |
|---|---|
| **Requirement ID:** T5.2.2<br>**Description:**<br>Team members must be briefed on testing operations and operational hazards prior to tests. | **Verification Plan:** All team members performing testing will be present for a pre-test briefing presentation covering safety procedure, material hazards, and necessary PPE approved by the safety officer. |
| | **Comments:** Pocket Safety Documents (See T5.1) will contain a condensed version of pre-test briefing for on-site reference. |
| **Status:** Incomplete | **Verification Test ID:** N/A |

| | |
|---|---|
| **Requirement ID:** T5.2.3<br>**Description:** Team members must be briefed on launch operations and procedures prior to any sub-scale or full-scale launch. | **Verification Plan**: All team members performing launch procedures will be present for a pre-launch briefing presentation covering PPE, launch hazards, and proper launch procedure. |
| | **Comments:** Pocket Safety Documents (See T5.1) will contain a condensed version of launch briefing for on-site reference. |
| **Status:** Incomplete | **Verification Test ID:** N/A |

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|---|---|
| **Requirement ID:** T5.3<br>**Description:**<br>All students working with powered machinery must demonstrate a clear and comprehensive knowledge | **Verification Plan:** Before operation, students must present verification of completion of requisite safety briefings, courses, or other material provided by the machine's holding group (Purdue BIDC, Zucrow Labs, Purdue ASL, etc). |

| | |
|---|---|
| of the machine and its requisite safety standards per the standards of the machining location. | **Comments:** Purdue BIDC requires online quizzes going over machine safety before the location is accessible to the student. |
| **Status:** Incomplete | **Verification Test ID:** N/A |

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|---|---|
| **Requirement ID:** T5.4<br>**Description:**<br>First aid equipment will be available and accessible at all launch day, construction, assembly, or test operations. | **Verification Plan:** Safety officer will be responsible for the upkeep and presentation of first aid kit. Kit's presence will be logged by safety officer, and initialed and dated by one witnessing team member. |
| | **Comments:** N/A |
| **Status:** Incomplete | **Verification Test ID:** N/A |

| | |
|---|---|
| **Requirement ID:** T5.5<br>**Description:**<br>Personnel hazards on launching field must be visibly marked, within the NAR minimum personnel distance, a 50 ft band in a straight line path from launch site to team observation site, and in the estimated drift area of the launch vehicle. | **Verification Plan:** Safety team members will perform sweep of surroundings before launch vehicle setup. Hazards will be denoted by flags outside the minimum cleared area and non-toxic non-flammable water soluble spray paint within the minimum clear area. |
| | **Comments:** Flags will be counted upon placement and recounted upon removal to ensure all flags are collected and accounted for. |
| **Status:** Incomplete | **Verification Test ID:** N/A |

## 6.3. Timeline

The timeline the PSP-SL team will be following is shown below. The timeline outlines the following events: **deadlines**, **launch opportunities**, **meetings or teleconferences with NASA officials**, **general team meetings**, and **miscellaneous events**.

| Date | Event | Date | Event |
|---|---|---|---|
| 08/22/2019 | NASA Releases 2020 Student Launch Handbook | 01/03/2020 | Final motor choice made for launch |
| 08/31/2019 | NAR Sport Launch @ Huber Heights, Ohio | 01/05/2020 | Possible Purdue SL general meeting |
| 09/01/2019 | Purdue SL general meeting | 01/10/2020 | CDR report, slides, and flysheet posted online by 8AM CDT |
| 09/02/2019 | LABOR DAY | 01/12/2020 | Purdue SL general meeting |
| 09/07/2019-09/08/2019 | Indiana Rocketry Launch | 01/13/2020 | CDR video teleconferences start |

| | | | |
|---|---|---|---|
| 09/08/2019 | Purdue SL general meeting | 01/11/2020-01/12/2020 | Tentative Indiana Rocketry Launch |
| 09/15/2019 | Purdue SL general meeting | 01/19/2020 | Purdue SL general meeting |
| 09/18/2019 | Proposal due to project office by 3PM CDT | 01/20/2020 | MLK JR. DAY |
| 09/22/2019 | Purdue SL general meeting | 01/22/2020 | CDR video teleconferences end |
| 09/28/2019-09/29/2019 | ROCI HPR Sport Launch @ Muncie, Indiana | 01/26/2020 | Purdue SL general meeting |
| 09/29/2019 | Purdue SL general meeting | 01/31/2020 | FRR Q&A |
| 10/03/2019 | Awarded proposals announced | 02/02/2020 | Purdue SL general meeting |
| 10/06/2019 | Purdue SL general meeting | 02/09/2020 | Purdue SL general meeting |
| 10/07/2019-10/08/2019 | OCTOBER BREAK | 02/08/2020-02/09/2020 | Tentative Indiana Rocketry Launch |
| 10/09/2019 | Kickoff, PDR Q&A | 02/16/2020 | Purdue SL general meeting |
| 10/12/2019 | ROCI HPR Sport Launch @ Cedarville, Ohio | 02/23/2020 | Purdue SL general meeting |
| 10/12/2019-10/13/2019 | Indiana Rocketry Launch @ Tab, Indiana | 03/01/2020 | Purdue SL general meeting |
| 10/13/2019 | Purdue SL general meeting | 03/01/2020 | Final day for full scale launch/Vehicle Demonstration Flight |
| 10/19/2019 | ROCI Sport Launch @ Muncie, Indiana | 03/02/2020 | Vehicle Demonstration Flight data reported to NASA |
| 10/20/2019 | Purdue SL general meeting | 03/02/2020 | FRR report, slides, and flysheet posted online by 8AM CDT |
| 10/25/2019 | Web presence established, URLs sent to project office by 8AM CDT | 03/06/2020 | FRR video teleconferences start |
| 10/27/2019 | ROCI Sport Launch @ Cedarville, Ohio | 03/08/2020 | Purdue SL general meeting |
| 10/27/2019 | Purdue SL general meeting | 03/14/2020-03/15/2020 | Tentative Indiana Rocketry Launch |
| 11/01/2019 | PDR report, slides, and flysheet posted online by 8AM CDT | 03/15/2020 | Possible Purdue SL general meeting |
| 11/03/2019 | Purdue SL general meeting | 03/16/2020-03/21/2020 | SPRING BREAK |
| 11/04/2019 | PDR video teleconferences start | 03/19/2020 | FRR video teleconferences end |
| 11/07/2019-11/10/2019 | SEDS SpaceVision in Tempe, Arizona | 03/22/2020 | Purdue SL general meeting |
| 11/09/2019 | ROCI Sport Launch @ Cedarville, Ohio | 03/23/2020 | Payload Demo Flight/Vehicle Demonstration Re-flight deadlines |
| 11/09/2019- | Tentative Indiana Rocketry Launch | 03/23/2020 | FRR Addendum submitted to NASA by |

| | | | |
|---|---|---|---|
| 11/10/2019 | | | 8:00 AM CDT (if needed) |
| 11/10/2019 | Purdue SL general meeting | 03/26/2020 | Launch Week Q&A |
| 11/15/2019-11/17/2019 | Midwest Power Launch @ Princeton, Illinois | 03/29/2020 | Purdue SL general meeting |
| 11/17/2019 | Purdue SL general meeting | 04/01/2020 | Travel to Huntsville, Alabama |
| 11/20/2019 | PDR video teleconferences end | 04/01/2020 | OPTIONAL – LRR for teams arriving early |
| 11/23/2019 | ROCI Sport Launch @ Cedarville, Ohio | 04/02/2020 | Official launch week kickoff and activities |
| 11/24/2019 | Purdue SL general meeting | 04/02/2020 | LRR (If not done on 04/01) |
| 11/25/2019 | CDR Q&A | 04/03/2020 | Launch week activities |
| 11/27/2019-11/30/2019 | THANKSGIVING BREAK | 04/04/2020 | Launch day |
| 11/30/2019 | ROCI Sport Launch @ Cedarville, Ohio | 04/04/2020 | Awards Ceremony |
| 12/01/2019 | Purdue SL general meeting | 04/05/2020 | Backup launch day |
| 12/07/2019-12/08/2019 | Tentative Indiana Rocketry Launch | 04/05/2020 | Possible Purdue SL general meeting |
| 12/08/2019 | Purdue SL general meeting | 04/12/2020 | Purdue SL general meeting |
| 12/14/2019-01/13/2020 | WINTER BREAK | 04/19/2020 | Purdue SL general meeting |
| 01/03/2020 | Final day for subscale launch | 04/27/2020 | PLAR posted online by 8AM CDT |

## 6.4. Line Item Budget

### 6.4.1. Full Scale Budget

| Item | Quantity | Cost (per item) |
|---|---|---|
| 48" long airframe sections (6" dia) | 3 | $46.25 |
| 14" long couplers | 3 | $4.89 |
| Bulkplates (t=1/8", 1/4" total w/ coupler b.p.'s, diam = coupler OD) | 6 | $9.00 |
| Coupler bulkplates (t=1/8", diam = coupler ID) | 6 | $9.00 |
| Nosecone (6" base dia) | 1 | $129.00 |
| Fiberglass sheet for fins (2'x2'x3/16") | 1 | $28.00 |
| Rail buttons | 3 | $0.00 |

| | | |
|---|---|---|
| Switch bands (6" dia) | 2 | $10.00 |
| Cesaroni L1115 | 1 | $292.99 |
| Motor casing | 1 | $366.99 |
| | Total | $1,098.40 |

### 6.4.2. Sub Scale Budget

| Item | Quantity | Cost (per item) |
|---|---|---|
| 3" 5:1 Ogive Compressed fiberglass nose cone with stepped tip | 1 | $63.95 |
| 76 mm Thin walled filament wound fiberglass airframe 48" | 1 | $80.00 |
| 76 mm coupler 8" and 12" | 2 | $18.00 |
| 3"x38mm G10 centering rings (x2), 1.6"/38mm G12 motor tube (subscale), AeroPack 38mm motor retainer | 1 | $54.00 |
| | Total | $233.95 |

### 6.4.3. Avionics Budget

| Item | Quantity | Cost (per item) |
|---|---|---|
| Classic Elliptical Parachute (24") | 1 | $64.00 |
| Rocketry Swivel (1,500 lb. Test) | 2 | $6.62 |
| 9V Battery Connectors | 1 | $3.18 |
| Latex Gloves | 1 | $9.95 |
| Hex Wrench Set | 1 | $15.20 |
| Terminal Blocks | 2 | $3.55 |
| Altimeter Mounting Posts | 4 | $3.83 |
| 3.7V 900 mAh LiPo Battery | 1 | $11.54 |
| FFFFG Black Powder (1 lb) | 2 | $18.99 |
| 1 ft E-Matches (80 ct) | 1 | $48.00 |
| 3 ft E-Matches (10 ct) | 1 | $19.50 |

| | | |
|---|---|---|
| Red 28 Gauge Stranded Wire (90 ft) | 1 | $4.50 |
| Black 28 Gauge Stranded Wire (90 ft) | 1 | $4.50 |
| Rocker Switches | 4 | $1.15 |
| | Total (Including Shipping) | $334.59 |

### 6.4.4. Payload Budget

| Item | Quantity | Cost (per item) |
|---|---|---|
| Pixhawk 4 Kit | 1 | $249.99 |
| Holybro Telemtry Transceiver | 1 | $23.99 |
| FrSky XSR RC Receiver | 1 | $18.99 |
| Nylon 6/6 Plate | 3 | $20.86 |
| Raspberry Pi Zero W | 2 | $5.00 |
| Nylon 6 Standoffs 6-32, 1” | 8 | $2.00 |
| Turnigy Aerodrive SK3 1740Kv | 6 | $18.03 |
| 7x4F Folding Propeller | 6 | $3.39 |
| FH45mm-6 Propeller | 6 | $5.00 |
| Turnigy Multistar 21A ESC | 6 | $9.81 |
| Turnigy 3600mAh 3S 30C LiPo | 2 | $27.65 |
| Toggle Switch and Cover | 4 | $2.95 |
| 15.6” EDP Display | 1 | $61.00 |
| 15.6” EDP Display Controller | 1 | $26.68 |
| 5mm LED Holder | 20 | $0.50 |
| 5mm LED Pack | 1 | $10.99 |
| Momentary Push Button Switch, 5 Pack | 2 | $11.69 |
| LED Push Button Switch, 5 Pack | 1 | $11.97 |
| 3 Pin Toggle Switch, 10 Pack | 1 | $7.99 |
| Rocker Switch, 15 Pack | 1 | $6.99 |

| | | |
|---|---|---|
| Raspberry Pi 4 2GB Ram | 1 | $45.00 |
| Taranis Q X7 | 1 | $97.99 |
| 3.2” TFT LCD Display | 1 | $6.99 |
| GCS Panels, Fiberglass | 1 | $50.00 |
| ELP 5MP Camera | 1 | $48.00 |
| Pimironi LiPo Sheet | 1 | $9.95 |
| 3.7v 2000mAh LiPo Battery | 1 | $12.95 |
| Leveling Servo | 1 | $32.99 |
| Leveling Clamp | 1 | $6.99 |
| Servo-Worm Coupler | 1 | $6.99 |
| Power Transmission Shaft | 2 | $1.09 |
| Linear Motion Shafts | 4 | $28.80 |
| Retaining Rings | 1 | $0.00 |
| Bushings | 12 | $0.86 |
| Turntable | 2 | $3.11 |
| RH Leadscrew | 1 | $16.60 |
| LH Leadscrew | 1 | $20.24 |
| Leadscrew Couplers | 1 | $8.69 |
| Eye Nut | 1 | $14.35 |
| Standoffs | 6 | $2.60 |
| Right Handed Nut | 1 | $31.42 |
| Left Handed Nut | 1 | $31.42 |
| Dual Shaft Stepper | 1 | $21.50 |
| Eye Nut Bolt | 1 | $5.69 |
| LiPo Charger with breakouts | 2 | $6.95 |
| XBee RF Module Kit | 1 | $99.00 |
| Teensy 4.0 Microcontroller | 2 | $19.95 |

| | | |
|---|---|---|
| Stepper Driver/Breakout board | 1 | $4.95 |
| Controller Battery | 1 | $9.95 |
| GY-521 Accelerometer | 1 | $4.99 |
| 6V Geared DC Motor | 2 | $10.99 |
| | Total | $1,673.73 |

### 6.4.5. Branding Budget

| Item | Quantity | Cost (per item) |
|---|---|---|
| Team Lead Polos | 12 | $13.99 |
| Outreach materials | 1 | $19.49 |
| | Total | $220.83 |

### 6.4.6. Safety Budget

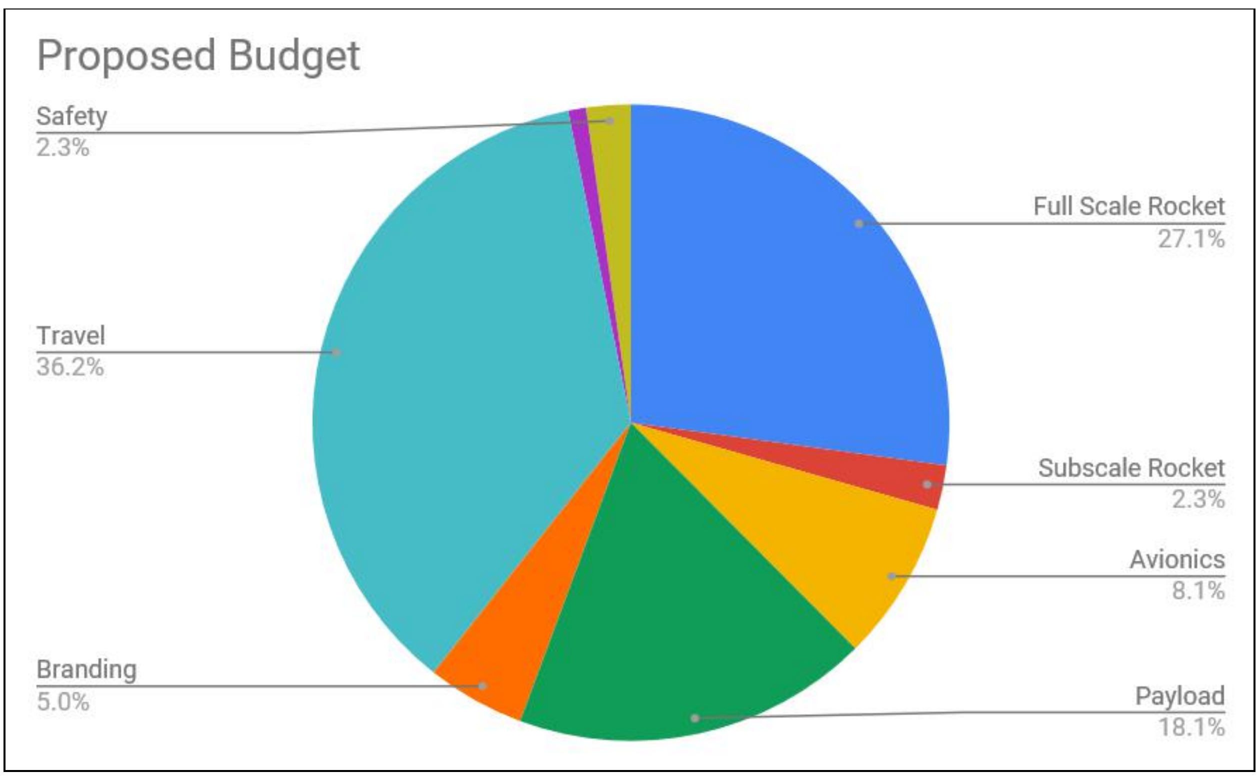
| Item | Quantity | Cost (per item) |
|---|---|---|
| Nitrile Gloves (box of 100) | 1 | 8.50 |
| Ear Plugs ((box of 200) | 1 | 20.55 |
| Canvas Gloves (pack of 12) | 1 | 18.84 |
| Safety Glasses (pack of 12) | 2 | 12.19 |
| Respiratory Face Masks (pack 20) | 2 | 9.99 |
| First Aid Kit | 1 | 34.99 |
| Welding Sleeves | 4 | 13.21 |
| Fire Extinguisher | 1 | 36.08 |
| Document Printing Kit | 1 | 6.59 |
| Spray on Chalk (pack of 3) | 1 | 12.61 |
| Flags (pack of 100) | 1 | 11.56 |
| | Total | $ 246.92 |

### 6.4.7. Travel Budget

| Item | Quantity | Cost (per item) |
|---|---|---|
| Hotel Room | 22 | $94 |
| Gas | 22 | $40 |
| Food | 22 | $47.82 |
| | Total | $4000 |

### 6.4.8. Budget Justification

Currently, the team has an overall budget of $11,050 for materials, branding, and travel. This was decided in a meeting in which all team leads discussed goals for the year and what needs to be achieved. A baseline budget was then determined for each subteam and values were rounded up to account for any potential problems each subteam may run into. This budget is believed to be sustainable and achievable. The budget is broken down into eight separate sections: $3000 for full scale, $250 for subscale, $900 for avionics, $2000 for payload, $550 for branding, $4000 for travel, $100 for outreach, and $250 for safety. The team's largest expense will be its travel budget, which accounts for the travel of 22 team members. This is a lower priority than the purchase of materials, but since the team has already raised more than enough for its materials plans have been made to fund the travel of 22 team members.

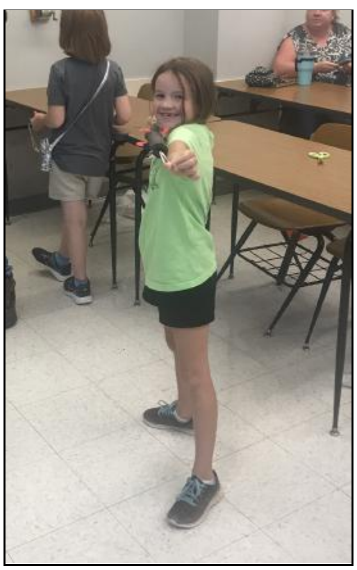


## 6.5. Funding Plan

The team's current funding plan follows four basic parts: working with Purdue department heads, crowdfunding, grant applications, and potentially working with Purdue Researchers to obtain part of the team's funding that way. The team is working with the AAE, ME, and ECE departments here at Purdue to achieve a part of its total budget. These departments have contributed 27.15% of the total budget. The team has raised $3,775 from its crowdfunding campaign and hopes to continue this until it has reached $5000 from the campaign. This would mean the team would have personally raised 45.25% of its total budget. Furthermore, the team has been applying to various grants and is working with Purdue professors for potential funding from their budgets as well. Originally, the team had planned to have 75% of its budget by December 14th, but as of October 27th, 2019, it has raised 75.79% of its total budget.

## 6.6. Completed Social Engagement Events

The team has currently completed two STEM engagement activities. The first event was done in partnership with the Purdue Space Day Ambassadors. The activities for that event were building foam launch vehicles and crater impact testing with various aged homeschool children. The purpose of the foam rocket activity was to help educate students about energy and launch vehicle propulsion through the construction of foam launch vehicles. During the crater impact testing activity, the students learned about what creates craters and how different size objects and different velocities affect a crater's size and shape. At this event there were 46 children as young as four and as old as thirteen. There were about 30 adults which accompanied the children.




The second event was with College Mentors for Kids, at which foam launch vehicles were once again created. The purpose of this event was to help educate the students and mentors about energy and launch vehicle propulsion through the foam launch vehicles. College Mentors for kids is an after school program that pairs elementary students with a college mentor, so the activity was able to reach not only the students but also their college mentors. There were 27 third and fourth graders and each one had their own mentor so there were also 27 college students with them. In the end the children and their mentors learned about launch vehicles and energy and were challenged to launch their launch vehicles at the best angle to get the farthest or the highest.

## 6.7. Plans for Future Social Engagement

In order to reach out to a majority of 3rd-8th students as well as others, team members will participate in the annual Purdue Space Day on Saturday, November 9th, where they will be in charge of running an activity for groups consisting of 30-50 students. They will create model launch vehicles, mock solar sails, and many other space-related projects with the kids. They will also be shown the different organizations around Purdue that are involved in STEM related projects. This will allow the kids to have an understanding of space exploration as well as the impact Purdue University has on the space industry. At Purdue Space Day, an astronaut will interact with the kids in attendance and give a presentation on the benefits of STEM involvement and the excitement of space exploration. Along with this event, the team will participate in more events with College Mentors for Kids and with Purdue Space Day Ambassadors.

# 7. Appendix A

## 7.1. NAR High Power launch vehicle Safety Code

- Certification. I will only fly high power launch vehicles or possess high power launch vehicle motors that are within the scope of my user certification and required licensing.
- Materials. I will use only lightweight materials such as paper, wood, rubber, plastic, fiberglass, or when necessary ductile metal, for the construction of my launch vehicle.
- Motors. I will use only certified, commercially made launch vehicle motors, and will not tamper with these motors or use them for any purposes except those recommended by the manufacturer. I will not allow smoking, open flames, nor heat sources within 25 feet of these motors.
- Ignition System. I will launch my launch vehicles with an electrical launch system, and with electrical motor igniters that are installed in the motor only after my launch vehicle is at the launch pad or in a designated prepping area. My launch system will have a safety interlock that is in series with the launch switch that is not installed until my launch vehicle is ready for launch, and will use a launch switch that returns to the "off" position when released. The function of onboard energetics and firing circuits will be inhibited except when my launch vehicle is in the launching position.
- Misfires. If my launch vehicle does not launch when I press the button of my electrical launch system, I will remove the launcher's safety interlock or disconnect its battery, and will wait 60 seconds after the last launch attempt before allowing anyone to approach the launch vehicle.
- Launch Safety. I will use a 5-second countdown before launch. I will ensure that a means is available to warn participants and spectators in the event of a problem. I will ensure that no person is closer to the launch pad than allowed by the accompanying Minimum Distance Table. When arming onboard energetics and firing circuits I will ensure that no person is at the pad except safety personnel and those required for arming and disarming operations. I will check the stability of my launch vehicle before flight and will not fly it if it cannot be determined to be stable. When conducting a simultaneous launch of more than one high power launch vehicle I will observe the additional requirements of NFPA 1127.
- Launcher. I will launch my launch vehicle from a stable device that provides rigid guidance until the launch vehicle has attained a speed that ensures a stable flight, and that is pointed to within 20 degrees of vertical. If the wind speed exceeds 5 miles per hour I will use a launcher length that permits the launch vehicle to attain a safe velocity before separation from the launcher. I will use a blast deflector to prevent the motor's exhaust from hitting the ground. I will ensure that dry grass is cleared around each launch pad in accordance with the accompanying Minimum Distance table, and will increase this distance by a factor of 1.5 and clear that area of all combustible material if the launch vehicle motor being launched uses titanium sponge in the propellant.
- Size. My launch vehicle will not contain any combination of motors that total more than 40,960 N-sec (9208 pound-seconds) of total impulse. My launch vehicle will not weigh more at liftoff than one-third of the certified average thrust of the high power launch vehicle motor(s) intended to be ignited at launch.
- Flight Safety. I will not launch my launch vehicle at targets, into clouds, near airplanes, nor on trajectories that take it directly over the heads of spectators or beyond the boundaries of the launch site, and will not put any flammable or explosive payload in my launch vehicle. I will not

launch my launch vehicles if wind speeds exceed 20 miles per hour. I will comply with Federal Aviation Administration airspace regulations when flying, and will ensure that my launch vehicle will not exceed any applicable altitude limit in effect at that launch site.

- Launch Site. I will launch my launch vehicle outdoors, in an open area where trees, power lines, occupied buildings, and persons not involved in the launch do not present a hazard, and that is at least as large on its smallest dimension as one-half of the maximum altitude to which launch vehicles are allowed to be flown at that site or 1500 feet, whichever is greater, or 1000 feet for launch vehicles with a combined total impulse of less than 160 N-sec, a total liftoff weight of less than 1500 grams, and a maximum expected altitude of less than 610 meters (2000 feet).
- Launcher Location. My launcher will be 1500 feet from any occupied building or from any public highway on which traffic flow exceeds 10 vehicles per hour, not including traffic flow related to the launch. It will also be no closer than the appropriate Minimum Personnel Distance from the accompanying table from any boundary of the launch site.
- Recovery System. I will use a recovery system such as a parachute in my launch vehicle so that all parts of my launch vehicle return safely and undamaged and can be flown again, and I will use only flame-resistant or fireproof recovery system wadding in my launch vehicle.
- Recovery Safety. I will not attempt to recover my launch vehicle from power lines, tall trees, or other dangerous places, fly it under conditions where it is likely to recover in spectator areas or outside the launch site, nor attempt to catch it as it approaches the ground.

## 7.2. NAR Minimum Distance Table

| Installed Total Impulse (Newton-Seconds) | Equivalent High Power Motor Type | Minimum Diameter of Cleared Area (ft) | Minimum Personnel Distance (ft) | Minimum Personnel Distance (Complex launch vehicle) (ft) |
|---|---|---|---|---|
| 0 — 320.00 | H or smaller | 50 | 100 | 200 |
| 320.01 — 640.00 | I | 50 | 100 | 200 |
| 640.01 — 1,280.00 | J | 50 | 100 | 200 |
| 1,280.01 — 2,560.00 | K | 75 | 200 | 300 |
| 2,560.01 — 5,120.00 | L | 100 | 300 | 500 |
| 5,120.01 — 10,240.00 | M | 125 | 500 | 1000 |
| 10,240.01 — 20,480.00 | N | 125 | 1000 | 1500 |
| 20,480.01 — 40,960.00 | O | 125 | 1500 | 2000 |

Note: A Complex launch vehicle is one that is multi-staged or that is propelled by two or more launch vehicle motors